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PHYSICAL AND GEOCHEMICAL OBSERVATIONS ON LAND RECLAMATION OF OPEN-PIT COAL MINES, ALBERTA AND BRITISH COLUMBIA

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PHYSICAL AND GEOCHEMICAL OBSERVATIONS ON LAND RECLAMATION OF OPEN-PIT COAL MINES, ALBERTA AND BRITISH COLUMBIA

Abstract

Previous studies dealing with the reclamation of open-pit coal mines in the Rocky Mountain Front Ranges and the Foothills have been concerned predominantly with vegetation and fertilizer trials. This study compares and contrasts geochemical and physical properties of natural regolith and rock waste. Data on these two materials have been assembled from field testing carried out during this study and from reclamation literature.

Regolith and rock waste found in coal-bearing areas are both stony sediments with comparable contents of clasts >2 mm; however, the <2 mm fraction of rock waste is generally coarser than that of regolith. Although large shale clasts in rock waste generally break down rapidly into smaller particles, these particles exceed the upper limit of the silt size range (64μm). Both rock waste and regolith are compacted during dumping and grading processes. High void ratios persist in both for an indeterminate period.

The mineralogy of regolith and rock waste adversely affects the results of determination of cation exchange capacity using ammonium acetate as an exchange reagent. A lithium acetate methodology is suggested. The chemistries of these two sediments are similar. The textures of both regolith and rock waste should be considered, however, when calculating cation exchange capacity and available nutrients. Because the <2 mm fraction in these sediments may constitute less than 50% by weight, levels of available nutrients may be half or less the levels indicated by analysis.

Résumé

Les études antérieures traitant de la restauration des sites d'exploitation houillère à ciel ouvert, dans la région des chaînons frontaux et des contrefonts des Rocheuses, ont principalement porté sur des essais de repeuplement par des plantes et sur des essais d'engraissement du sol. Dans la présente étude, on compare les propriétés géochimiques et physiques du régolithe naturel et des stériles. On a réuni les données sur ces deux matériaux à la suite d'essais réalisés in situ durant cette étude et à partir d'autres documents sur la restauration des sites.

Le régolithe et les stériles observés dans les régions houillères sont tous deux des sédiments pierreux contenant des quantités comparables de fragments rocheux >2 mm; toutefois, la fraction <2 mm des stériles est généralement plus grossière que celle du régolithe. En règle générale, les plus gros fragments composés de schiste argileux et contenus dans les stériles se fragmentent rapidement en particules plus petites, mais ces dernières dépassent la limite granulométrique supérieure des limons (64 μm). Les stériles et le régolithe sont tassés durant les phases de déversement et de granoclassement. Dans ces deux matériaux, des taux de porosité élevés persistent pendant une période plus ou moins longue.

La minéralogie du régolithe et celle des stériles influencent d'une manière défavorable les résultats de la détermination de la capacité d'échange cationique, lors de l'utilisation de l'acétate d'ammonium comme réactif d'échange. On propose l'adoption d'une méthode basée sur l'emploi d'acétate de lithium. La chimie des deux sédiments considérés est similaire. Il faut toutefois tenir compte des textures du régolithe et des stériles, lorsqu'il s'agit de calculer la capacité d'échange cationique et les concentrations d'éléments nutritifs disponibles. La fraction <2 mm de ces sédiments pouvant représenter moins de 50% du matériau en poids, les concentrations d'éléments nutritifs disponibles peuvent atteindre la moitié ou moins des valeurs indiquées par l'analyse.

SUMMARY

Open-pit coal mining in the Rocky Mountain Front Ranges and Foothills unavoidably disrupts soil and underlying bedrock and totally eliminates vegetation within the mine site. Reclamation seeks to restore disrupted lands to a state in which they can again support a self-perpetuating vegetal cover following the cessation of mining. Much reclamation research related to open-pit coal mining in this region has been oriented toward botanical trials. Studies have sought to determine which varieties of plants grow best on various substrates and at what levels of chemical fertilization. In this study, the chemistry, mineralogy, and physical properties of materials available for reclamation were investigated in and around present, past, and future open-pit coal-mining sites. The aims of this study were more effective evaluation of natural soils and rock waste as materials upon which vegetal covers can be established and evaluation of the length of time required for reclaimed rock wastes to approach the physical properties of undisturbed soils.

Both rock waste and natural soils are stony in the areas of open-pit mines and prospects. However, rock wastes contain a significantly lower content of the chemically active silt and clay fraction relative to natural soils. The silt and clay content of rock waste is unlikely to increase through natural physical breakdown within a human lifetime. The content of sand size particles does increase rapidly in rock waste. Large clasts may disaggregate entirely into sand and pebble size particles within a few decades. The dumping and grading of rock wastes and stockpiled natural soils compacts these materials to a high degree. High soil density makes root growth difficult. High density in reclaimed rock waste and soil persist for at least a decade.

Cation exchange capacity is a measure of the capacity of a soil to adsorb and release nutrients essential to plant growth. Vermiculite, a clay mineral, is present within bedrock and natural soils around active and prospective coal-mining areas. The presence of this mineral causes erroneous results when the cation exchange capacity of soil and rock wastes is determined using ammonium acetate as an extracting reagent. Carbonate minerals, common in the rocks and soils of this region, also contribute to erroneous results when standard methodology is used to determine cation exchange capacity. A methodology was developed as a part of this study to eliminate these problems by using lithium acetate as an extracting reagent and by the analysis of second extractions to determine the erroneous contribution of cations through dissolution of carbonate minerals.

SOMMAIRE

Il est inévitable que l'extraction du charbon à ciel ouvert dans les chaînons frontaux et les contreforts des Rocheuses perturbe le sol et le socle sous-jacent, et élimine totalement la végétation à l'intérieur de l'emplacement de la mine. Les efforts de restauration des sites ont pour but la remise en état des terrains perturbés, de sorte qu'ils puissent à nouveau porter une couverture végétale capable de se renouveller continuellement dès la fin des activités minières. Dans cette région, une grande partie de la recherche sur la restauration des sites d'extraction du charbon à ciel ouvert a porté surtout sur les essais botaniques. En réalisant ces études, on a cherché à déterminer quelles variétés de végétaux se développent le mieux sur les divers substrats, et à quelles concentrations d'engrais chimiques. La présente étude met l'accent sur la chimie, la minéralogie et les propriétés physiques des matériaux susceptibles de servir aux efforts de restauration, dans les emplacements actuels, passés et futurs d'exploitation du charbon à ciel ouvert. Dans cette étude, on a cherché à évaluer de façon plus efficace dans quelle mesure les sols naturels et les stériles se prêtent à l'établissement d'une couverture végétale, et l'intervalle de temps nécessaire pour que les propriétés physiques des stériles faisant l'objet d'efforts de restauration se rapprochent de celles des sols non perturbés.

Les stériles et les sols naturels sont pierreux dans les régions des mines à ciel ouvert et des gîtes possibles. Toutefois, les stériles contiennent une proportion beaucoup plus faible des fractions limoneuses et argileuses chimiquement actives, comparativement aux sols naturels. Il est peu probable que la teneur en limon et argile des stériles augmente par décomposition physique naturelle pendant une durée correspondant à celle d'une vie humaine. Toutefois, la teneur en particules sableuses augmente rapidement dans les stériles. Les plus gros fragments peuvent entièrement se désagréger en particules de la taille du sable et de galets en l'espace de quelques décennies. Le déversement et le granoclassement des stériles et des sols naturels accumulés ont pour conséquence le fort tassement de ces matériaux. La densité élevée du sol rend difficile la croissance des racines. Les stériles et sols remis en état conservent une densité élevée pendant au moins une décennie.

La capacité d'échange cationique est une mesure de la capacité d'un sol à adsorber et libérer les éléments nutritifs essentiels à la croissance des végétaux. Il existe de la vermiculite, minéral argileux, à l'intérieur de la roche de fond et des sols naturels aux alentours des zones d'exploitation minière actuelles et possibles de la houille. En raison de la présence de ce minéral, on obtient des résultats erronés, lorsque l'on détermine la capacité d'échange cationique du sol et des stériles en employant de l'acétate d'ammonium comme réactif d'extraction. Étant donné que les roches et sols de cette région contiennent souvent des minéraux carbonatés, on obtient aussi des résultats erronés lorsque l'on emploie les méthodes normalisées pour déterminer la capacité d'échange cationique. Dans le cadre de la présente étude, la méthode mise au point permettra d'éliminer ces problèmes; il suffit d'utiliser de l'acétate de lithium comme réactif d'extraction, et d'analyser le produit d'une seconde extraction pour déterminer dans quelle mesure les cations faussent les résultats suite à la dissolution des minéraux carbonatés.

The textures of regolith and rock wastes should be considered when calculating cation exchange capacity. Because this analysis is carried out on the fine fraction of a sample, a cation exchange capacity value should be weighted according to the content of the fine fraction within the soil or rock waste, which is not done routinely.

Il faut tenir compte des textures du régolithe et des stériles, lors du calcul de la capacité d'échange cationique. Étant donné que l'on effectue cette analyse sur la fraction fine d'un échantillon, il faut pondérer la valeur de la capacité d'échange cationique selon la concentration de la fraction fine dans le sol ou les stériles, ce qui ne se fait pas habituellement.

INTRODUCTION

Historical background

Throughout the Canadian Cordillera, coal has been mined on widely ranging scales at various times since the mid-nineteenth century. Mining began on Vancouver Island in 1849 where coal was used for domestic purposes and steamship fuel (Fig. 1). In the 1890s, railroad construction provided the impetus for coal exploration and development in the Rocky Mountain Front Ranges and Foothills of what is now Alberta and British Columbia. Coal mining and exploration prospered for the next 50 years. Coal began to be displaced by oil as a fuel for ships by the 1920s and for railroad locomotives by the late 1940s as diesel-electric replaced steam-powered motive systems. By the mid 1950s, oil and natural gas displaced coal as sources of domestic heat and light leaving only a small market for coking coal. In Alberta, many former coal-mining towns such as Mountain Park and Coalspur were abandoned and razed. Those that survived did so because of skeleton mining operations and the exploitation of other natural resources, such as timber or tourism.

By the mid 1960s, increasing demands for metallurgical coal, primarily by the Japanese steel industry, led to a resurgence of coal-mining activity in the Rocky Mountain coalfields where metallurgical coal is abundant. Initial rebirth of the industry took place in the historic coal-mining areas of the Crowsnest Pass and Elk Valley in Alberta and British Columbia and in the Luscar Cadomin Coal Basin of Alberta. A new mining centre in northern Alberta at Grande Cache was developed in the late 1960s and early 1970s and similar development in northeastern British Columbia was underway by the early 1980s. Coal from these areas not only supplies industry in western Pacific rim countries but also markets for thermal and metallurgical coal in eastern Canada and in Europe.

The scale of coal operations of the 1980s contrasts strongly with those of the first half of the century. Whereas underground mining was formerly the norm, more than 90% of current production now comes from surface mining operations (Coal Task Force, 1976). Machinery to blast and haul rock and coal has grown in capacity to the scale of 180 tonne trucks and unit trains of 90 tonne coal cars. As a result, such operations as the Harmer Ridge operation of Westar Mining Ltd. near Sparwood, British Columbia, now virtually level mountains and fill in valleys with discarded overburden.

Major alterations to the landscape along with the attendant infrastructure of haul and exploration roads and townsites have enormous effects on the land, air, and water in and around these operations. Since the late 1960s, legislation has been enacted by the governments of Alberta and British Columbia to ensure minimum standards of air and water quality in and around industrial areas. Also, legislation and government policy have been enacted to ensure that lands disturbed by extractive industries are restored to states comparable to their original conditions.

Restorations are difficult. Blasting and dumping activities often leave steep slopes composed of angular, broken rock. The regolith consisting of the pre-existing soil and its glacial or colluvial parent materials are typically thin and difficult to remove from steep mountain sides and to stockpile prior to mining. Consequently, reclamation must often be carried out on rock waste.

Reclamation research in coal-bearing areas of the northern Rocky Mountain Front Ranges and Foothills has been primarily botanical, that is, establishing which varieties of plants grow the best on various substrates and under what levels of chemical fertilization. Comparatively little work has been devoted to investigating the chemistry and physical properties of natural and reclaimed soils. The work that has been done has been specific to individual mine sites. It has focused on overburden inventories, that is, the systematic determination of the volumes of noncoal rock and unconsolidated deposits to be disturbed by mining and their relevant physical and chemical properties.

Definitions

In related disciplines, slightly different meanings are often assigned to the same terms. Because of the multidisciplinary nature of this study, the following terms which are particularly significant to the subject of this report, are defined here for the reader. Other terms that may be unfamiliar are in bold print at first use in the text and are defined in the Glossary.

agronomics: plant varieties used for the rapid revegetation of a disturbed and denuded site.

overburden: all the rock and regolith overlying a coal seam.

regolith: the mantle of unconsolidated sediments or disaggregated or partly disaggregated bedrock that overlie unweathered and intact bedrock. Regolith includes both soil and parent material.

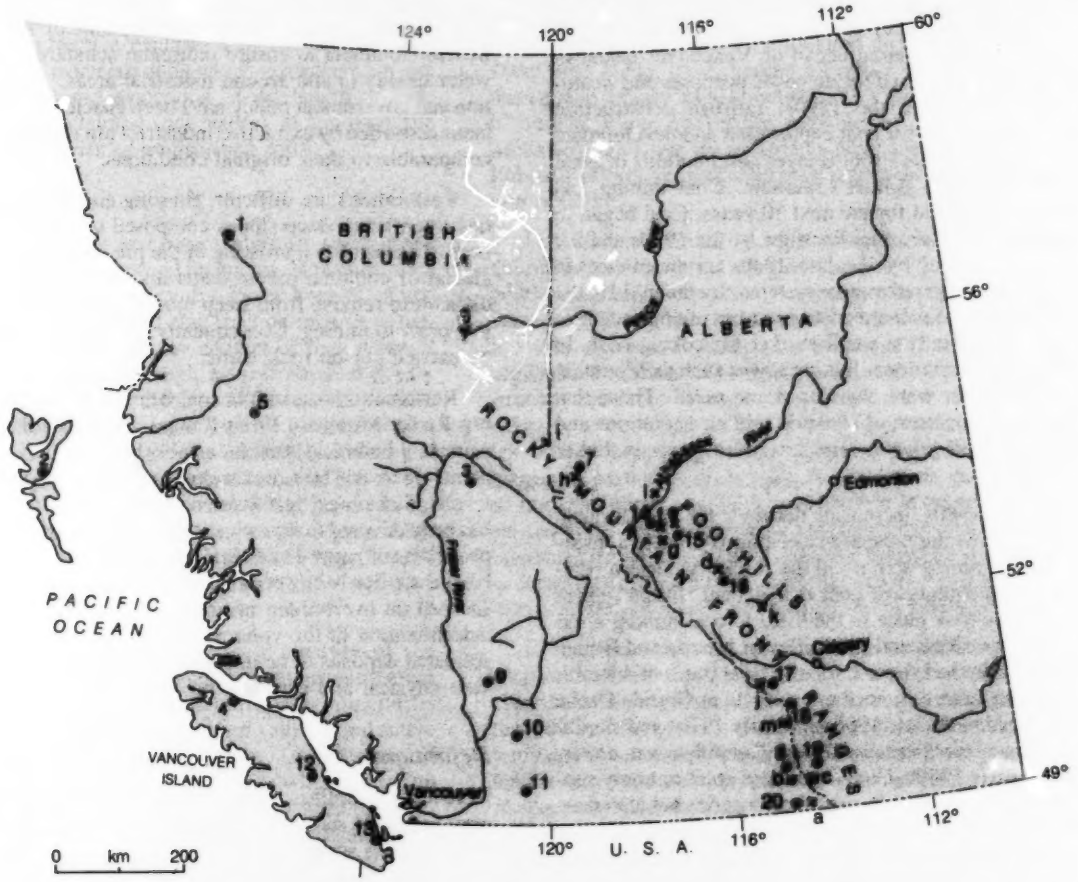
rock waste: coarse, granular debris created by the blasting, hauling, and dumping of unweathered rock overlying a coal seam.

soil: natural material consisting of layers or horizons of mineral and/or organic constituents of variable thicknesses, which differ from the parent material in their morphological, physical, chemical, and mineral properties and in their biological characteristics (Joffe, 1949).

parent material: bedrock or unconsolidated sediment that underlies, and from which, soil is developed.

Previous work

An extensive literature exists world-wide for the **reclamation** of lands disturbed by open-pit coal mining and other analogous activities, a summary of which is beyond the scope of this report. Since 1978, the Office of Arid Lands Studies of the University of Arizona has compiled a bibliography of current reclamation literature under the sponsorship of several departments of the United States government. This reference bulletin, known as SEAMALERT, as of 1984 is the most complete listing of reclamation literature in existence, and is updated several times each year.



• MAJOR COAL DEPOSITS

1 Groundhog
2 Graham Island
3 Bowron River
4 Suquash
5 Telkwa
6 Peace River
7 Grande Cache
8 Crowsnest Pass (B.C.)
9 Hat Creek
10 Merritt
11 Similkameen
12 Cumberland
13 Nanaimo
14 Luscar-Cadomin
15 Mountain Park
16 Brazeau
17 Cascade
18 Highwood
19 Crowsnest Pass (Alberta)
20 Sage Creek

× SAMPLING AND/OR TEST SITES

a Sage Creek
b Hosmer, McGillivray, Hanmer Ridge, C-Seam
c York Creek
d Nordegg
e Coal Valley
f Cardinal River Mine/ Cadomin
g Mountain Park
h Grande Cache
i Saxon Ridge
j Marmot Creek
k Deer Creek
l Obed Mountain
m Elk Valley

Figure 1. Major coal-bearing areas of the Canadian Cordillera in Alberta and British Columbia.

Studies directly applicable to reclamation of coal wastes in the Canadian Rocky Mountains are limited. Results of studies carried out in the Appalachians of the United States reflect acid-producing substrates and mild, humid climate. Neither factor affects coal mine reclamation in the Rocky Mountains. Studies from the Canadian Prairies and the Great Plains of the United States have involved sites of low relief, arid climate, and saline bedrock. Such characteristics are largely unapplicable to the Canadian Rocky Mountains. Hubbard and Bell (1977) assembled an annotated bibliography of studies dealing with reclamation of disturbed lands in northern and mountainous environments up to the end of 1976. Most previous studies have concentrated on trials of agronomic grasses and legumes and the studies of soil development and nutrient cycling in reclaimed soils, e.g., Etter (1971), Dillion (1973), and Lesko et al. (1975) at Luscar; Macyk (1974) and Macyk and Stewart (1977) at Grande Cache; Berdusco and Milligan (1978), Ziemkiewicz (1977, 1979,) and Ziemkiewicz and Northway (1978) in the Crowsnest Pass area. As of 1984, studies of longest duration have been continuing reclamation studies carried out at Grande Cache by the Alberta Research Council of Alberta under the direction of T. Macyk and by the Reclamation Division of B.C. Coal Ltd. (now Westar Mining Ltd.) in the Sparwood area of the Crowsnest Pass/Elk Valley in British Columbia. These two programs have amassed more than 20 years of reclamation research in the Rocky Mountain Front Ranges and Foothills. Results of these studies have shown aspect, elevation, microclimate, and latitude to play major roles in determining the success and choice of agronomic species for revegetating areas disturbed by open-pit coal mining.

Compared with botanical and biochemical reclamation research, studies concerned with physical and geochemical aspects and problems associated with reclamation are less common. Most of these studies are unpublished consultants' reports to mining companies as part of environmental impact studies which are required by law prior to mine development. The work that has been done has been on a mine site by mine site basis and has focused on overburden inventories. With respect to published studies, Harrison's (1973a, b, 1974a, b, 1977) work led to a number of concepts that have found application by the coal industry. Harrison found that overburden waste dumps, though usually stable at the **angle of repose** of approximately 37°, underwent significant surface **creep** and **ravelling**. This movement was significant enough to prevent the growth of vegetation. He determined that creep essentially ceases on dump slopes of 25°-30°. He gave the name **"biological angle of repose"** to this slope range. Harrison measured **bulk densities** and **textures** of natural overburdens, dump, and lagoon sediments and related these properties to the lithologies of the rock fragments composing these sediments. He conducted infiltration studies on these sediments and determined their moisture contents. He found moisture stress to plants to be a distinct problem on rock waste dumps because of high **infiltration rates** and low **capillary rise** which characterize this material. Harrison took temperature readings on dump slopes and found surface temperatures to range up to 72°C on south-facing slopes during the growing season. His measurements suggested the value of creating **microrelief** on the reclaimed surface and of establishing nursery crops on dumps to shade small shrubs and trees from the scorching effects of the sun.

McCoy (1975) found rock waste to contain only a small fraction of particle sizes (18.5% by weight on average) which were <2 mm in diameter. Thus much rock waste had little value as a growth medium. McCoy also noted the low **cation exchange capacity** of the fine fraction of rock wastes and recommended that materials with higher capacity for cation exchange be added to rock waste prior to seeding to facilitate retention of fertilizers.

Root (1976) observed the nature and rates of physical breakdown of rock wastes on dumps near Cadomin. He found wind erosion to be a significant process on the spoil, and moisture stress to be a distinct impediment to reclamation

A satellite reconnaissance of mine sites across Canada was carried out by Murray (1977). Included in the study were the results of sampling programs for rock waste texture, bulk densities, grain density, and chemistry at several dump sites in the Crowsnest Pass, British Columbia, and at the McIntyre Mine (now Smokey River Coal Ltd.) in Grande Cache, Alberta.

Headdon (1980) investigated physical characteristics of rock wastes at the York Creek Mine site south of Blairmore, Alberta, in the Crowsnest Pass area. He found natural revegetation to be most advanced on glacial till and least on sandstone rock waste. He found high ground temperatures and moisture stress to be the most significant factor in limiting plant growth on rock waste.

Published studies of the geochemistry of rock waste in the Rocky Mountain Front Ranges and Foothills have been concerned primarily with their effects on the chemistry of streams draining waste dumps, e.g., Hackbarth (1979), Harrison (1977), Jackson (1982), and Root (1976). Devenny and Ryder (1977) examined rock chemistry in the Luscar Formation to evaluate the potential hazard posed by these wastes to water chemistry around dump sites.

STUDY DESIGN

Setting

The Canadian Rocky Mountain Front Ranges and Foothills form a long, narrow belt stretching from southwestern Alberta and southeastern British Columbia, northwest to northeastern British Columbia (see Fig. 1). The Foothills are composed of northwest-trending folded and thrust faulted Mesozoic and lower Cenozoic clastics. Surface elevations range from about 1000 m in the Foothills to almost 3000 m in the Rocky Mountain Front Ranges. The region is characterized by short, cool summers and long, severe winters (Table 1), which are moderated sporadically by chinook winds. Precipitation generally increases with elevation and distance westward into the Foothills and Front Ranges. Mean annual temperature generally decreases with increasing elevation and latitude.

Table 1. Climatic data for selected locations in the Rocky Mountain Front Ranges and Foothills, 1951-1980[1]

Location	Elevation (m)	Position	Mean daily temperature (°C)		No. days with frost[2,3]	Mean total rain (cm)	Mean total snow (cm)
			Jan.	July			
Fernie	1011	49°31'N, 115°03'W	-8.1	16.3	185	73.0	39.6
Coleman	1341	49°38'N, 114°35'W	-9.4	14.6	198	35.1	21.8
Kananaskis	1390	51°02'N, 115°03'W	-10.2	14.1	220	36.0	29.2
Rocky Mountain House	1015	52°23'N, 114°55'W	-13.0	15.3	NA	38.9	18.8
Jasper	1061	52°53'N, 118°04'W	-12.8	15.1	213	27.9	15.2
Robb	1130	53°14'N, 116°58'W	-13.4	13.8	NA	41.6	20.8
Hinton	1014	53°24'N, 117°33'W	-14.4	14.4	218	34.8	13.6
Edson	924	53°35'N, 116°25'W	15.0	-12.5	NA	39.5	19.6
Grande Cache	1250	53°54'N, 119°06'W	-12.3	13.8	NA	36.9	27.8
Fort St. John	695	56°14'N, 120°44'W	-17.7	15.6	NA	28.9	22.2

[1] Data from Environment Canada, 1980.
[2] Data from the period 1941-1970 (Environment Canada 1973).
[3] NA = not available.

Vegetation throughout this region is predominantly montane forest in valleys, subalpine forest at higher elevations, and alpine tundra above the timberline. The timberline decreases progressively in elevation from about 2130 m at the latitude of Crowsnest Pass to about 1830 m at the latitude of Grande Prairie (see Fig. 1). Soils vary from **Luvisols, Podzols,** and **Brunisols** at lower, forested sites to **Regosols** at higher elevations. Gleyed and organic soils occur locally in areas of poor or seasonally poor drainage. Parent materials range from siliceous sandstones to carbonate-rich till (Beke, 1969).

Two distinct structural belts have yielded coal within the area. From west to east they are the inner Foothills and outer Foothills (Latour, 1972). In the outer Foothills, coal production has been principally from the Upper Cretaceous "Coalspur Beds" (MacKay, 1949) in the Coal Valley area (Fig. 2). This unit outcrops in a narrow belt between the North Saskatchewan and Athabasca rivers. The coal produced from this area is typically high-volatile bituminous in rank. Although the coal-bearing units within this belt have been folded and faulted, relative relief is low, generally less than 200 m. The inner Foothills belt extends westward to the mountains and includes parts of the Rocky Mountain Front Ranges. Within the belt are major folded and faulted structures which are expressed as high ridges that can commonly be traced many kilometres. Relative relief generally ranges between 500 and 1000 m. Coal-producing formations are Lower Cretaceous in age. Approximately south of the latitude of Red Deer, the Kootenay Formation produces coal, whereas to the north of it, the Luscar Formation is productive. Coal from the inner Foothills belt is low- to medium-volatile bituminous in rank.

Aims

In this study, the chemistry, mineralogy, and physical properties of materials available for reclamation were investigated within a number of coal-bearing areas of the Rocky Mountain Front Ranges and Foothills. The study was designed to provide further insights into the physical and chemical properties of materials for reclamation and methods by which they are measured. The results of this study should allow more effective evaluation of these materials and the success of reclamation activities.

Fieldwork

Field work for this study was carried out during the summers of 1977 and 1978. The 1977 work was primarily a reconnaissance of orphaned and active mine sites and some preliminary sampling (see Fig. 1). Materials for reclamation can be obtained from two general sources — regolith and rock waste. Field testing of regolith and rock waste and further sampling were carried out during 1978 (Fig. 3-5). Table 2 summarizes tests and sampling at each site. Specific methods of sampling and testing are described in the appropriate sections of this report.

Table 2. Site characteristics and summary of physical and chemical tests carried out

Site	Location	Elevation (m)	Vegetation[1]	Underlying bedrock[2]	Material sampled[3]	Tests[4]	Nearest source of long-term climatic data[5] (see Table 1)	General description
Sage Creek, B.C.	49°06'N 114°36'W	~1370	S/P	A	R	T,C,D	F	Proposed site of Sage Creek mine
Elk Valley, B.C.	50°50'N 114°54'W	~1524		A	R	T,C	F	Proposed site of Elco mine
Hosmer, B.C.	49°35'N 114°57'W	~1067	S/P	A	W	T,D P,A		Underground mine-mouth tip
Harmer Ridge, B.C.	49°40'N 114°50'W	~2120	S/P	A	R/W	T,D P,A	F/C	Top of knoll with slope < 5°; reclaimed dump with slope 5-10°
Lower C-Seam, B.C.	49°39'N 114°48'W	~1600	S/P	A	R/W	T,D A	F/C	Reclaimed open-pit mine and dump
McGillivray, B.C.	49°38'N 114°46'W	~1420	S/P	A	R/W	T,D,P A	F/C	Reclaimed open-pit mine and dump
York Creek, Alta.	49°35'N 114°31'W	~1585	S/P	A	R/W	T,C	C	Sampled rock waste and nearby regolith
Brazeau, Alta.	52°29'N ~116°05'W	~1370	S/P	E	R/W	T,C	RMH	Sampled rock waste and nearby regolith
Cardinal River Mine, Alta.	53°05'N 117°25'W	~1670	S/P	E	R/W	T,D,C A	H	Open-pit mine dump
Mountain Park, Alta.	52°55'N 117°20'W	~1774	S/P/T	E	W	T,D,C A	H	Open-pit mine dump
Grande Cache, Alta.	54°03'N ~119°09'W	~1067	S/P	E	R	T,C	GC	Regolith near open-pit mine
Saxon Ridge, B.C.	54°20'N ~120°05'W	1220 -1680	T	G	R	T,C	FSJ	Regolith at proposed open-pit mine site
Obed Mtn., Alta.	54°35'N ~116°30'W	~1524	S/P	C	R	T,C	H	Regolith at proposed open-pit mine site on hill top
Coal Valley, Alta.	53°05'N 116°47'W	1280	S/P	C	R	T,C	H/RMH	Regolith adjacent to open-pit mine site

[1]S — spruce forest; P — pine forest; T — alpine tundra.
[2]A — Kootenay Group; C — "Coalspur Beds"; E — Luscar Formation; G —Gething Formation
[3]R — regolith; W — rock waste.
[4]A — sediment chemistry; C — clay mineralogy; D —bulk density
P — Proctor test; T — texture.
[5]F — Fernie; C — Coleman; RMH — Rocky Mountain House; H — Hinton;
GC — Grande Cache; FSJ — Fort St. John.

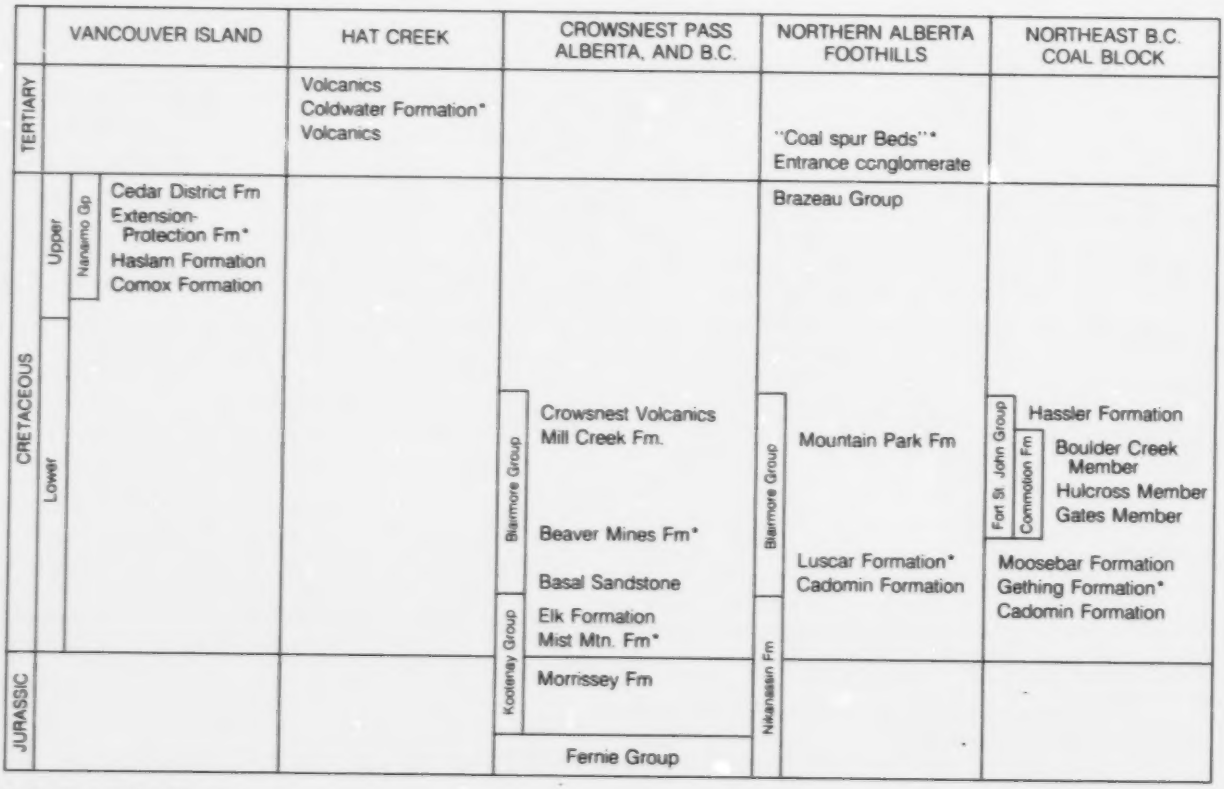
REGOLITH

Mapping and studies of the physical and chemical properties of regolith in and around coal-bearing areas of the Rocky Mountain Front Ranges and Foothills have been carried out primarily in conjunction with experimental watersheds and environmental baseline studies prior to mining. Of such studies, those by Beke (1969) in the Marmot Creek and the Deer Creek basins (Fig. 1) and by Cardinal River Coals Ltd. (1977 unpublished) are most significant (Table 3). However, in both studies most of the sampling was concentrated on the soil component of regolith rather than on the parent material. Parent material represents a much greater percentage by volume of the total regolith and is, therefore, a more abundant material for reclamation.

Texture

Regolith in coal-bearing areas of the Rocky Mountain Front Ranges and Foothills is typically stony. Table 4 summarizes data on the coarse (weight percent >2 mm) fractions of regolith (both nonorganic soil and parent material) from coal-bearing areas. The stoniness of these sediments reflects the origin of the regolith as till and colluvium. Stone-free or slightly stony regolith is found only locally where it is of glaciolacustrine or lacustrine origin. The generally less stony regolith in the Deer Creek area probably reflects the comparatively larger content of shale in the bedrock and lower relief of this outer Foothills site. During this study, regolith was sampled from 47 pits and road cuts located at 14 sites including active, orphaned, and prospective mine sites from the Crowsnest Pass area north through the Foothills to the Saxon Ridge area (Fig. 1 and Table 2). The >2 mm fraction of till and of colluvium sampled at these sites are coarser than the values determined by Beke (1969) in his detailed sampling of two study sites. This difference may result from a larger particle size limit (32 mm) used in this study. Beke did not specify the upper size limit used in his sampling.

Figure 6 plots soil textures of samples of regolith analyzed by Beke (1969) from the Deer Creek and Marmot Creek basins and samples from the Cardinal River Coals Ltd. (1977 unpublished) study. Regoliths from these sites were colluvium, till, and glaciolacustrine deposits. Figure 7 is a similar plot of regolith deposits obtained from 14 test sites (listed in Table 2). Both till and colluvial regolith fall predominantly in the silt loam, loam, clay loam, or sandy loam region of both soil texture plots. Samples falling in the clay region of the chart were taken from local glaciolacustrine deposits.



* denotes coal-bearing unit

Figure 2. Coal-bearing formations in the Canadian Cordillera of Alberta and British Columbia.

Table 3. Previous studies including extensive physical or chemical analysis of regolith in coal-bearing areas, Rocky Mountain Front Ranges and Foothills

Site	Study	Location	Elevation (m) Max.	Elevation (m) Min.	Area (km^2)	Vegetation[1]	Underlying[2] bedrock	Origin of regolith	Nearest source of long-term climatic data (Table 1)[3]	General description
Marmot Creek basin	Beke (1969)	115°12'W 50°48'N	2790	1580	10	S/P/AT	A	Colluvium, till, bedrock	K	Basin is almost entirely in moderate-to-steep slopes
Deer Creek basin	Beke (1969)	51°53'N 115°00'W	1700	1360	7	P	B	Till with minor glacial fluvial and glacio-lacustrine sediments	H,J	Basin is almost entirely in gentle-to-moderate slopes
Cardinal River Mine	Cardinal River Coals Ltd. (1977, unpublished)	53°05'N 117°25'W	1830	1490	10	S/P/F	C	Till, colluvium, minor fluvial gravels and organic deposits	H,J	Mine site characterized by gentle-to-steep slopes

[1] S — spruce forest; P — pine forest; AT — alpine tundra; F — subalpine fir.
[2] A — predominantly Mesozoic clastics including the coal-producing Kootenay Formation. Higher areas of the basin are underlain by Paleozoic carbonates and clastics. B — Tertiary clastics. Though not productive of coal in this basin, they are similar to coal-producing units in the Coal Valley area. C — Paleozoic carbonates and Mesozoic clastics including the coal-bearing Luscar Formation.
[3] K — Kananaskis; H — Hinton; J — Jasper.

Bulk density

Dry bulk density is an indirect measure of void space present in regolith. Regolith with a high value for bulk density provides a more difficult medium through which plant roots must extend to obtain water and nutrients than does regolith with lower bulk density (Lull, 1959, p. 24). Excavation, storage, and regrading of regolith during mining operations compacts the regolith and, thus, increases its bulk density. Consequently, the dry bulk densities of both undisturbed and reclaimed regolith are useful variables to measure. They can be used to evaluate the degree of compaction of regolith after it has been stockpiled and regraded over disturbed terrain. They can also indicate the degree of development of **soil structure** following reclamation and follow-up testing of reclaimed regolith. However, the bulk density values determined for regolith are probably most useful in a relative sense. Regolith includes pebble and larger clasts (>4 mm) around which plant roots must grow rather than extend through. These high-density rock fragments cause bulk density values of the entire regolith to be greater than those of matrix between stones in which root growth actually takes place.

Beke (1969) measured bulk densities of regolith in the Marmot Creek and Deer Creek watersheds using a tube sampler (Fig. 8A, 8B). Zero depth is taken as the base of the **organic** (L-H) **soil horizons** at the top of the mineral soil in these figures. These natural soils show an overall increase in bulk density with depth. This progressive consolidation would be expected with increasing overburden

Table 4. Coarse fraction particles in regolith from undisturbed coal-bearing areas

Study	Site[1]	Pits	Samples	Weight % $\bar{x}$	Weight % s	Weight % Max.	Weight % Min.
Beke (1969)[2]	M	35	104	14.8	15.5	68	0
Beke (1969)[2]	D	9	31	7.0	5.9	24	2
This study[3]	F	45	47	32.9	13.1	67	3

[1] M — Marmot Creek basin; D — Deer Creek basin; F — orphaned mine sites and prospective mine sites from the Crowsnest Pass area, Alberta and British Columbia, north through the Foothills to the Kakwa River basin.
[2] Upper size limit of coarse fraction not specified. The >2 mm fraction simply called "gravel."
Samples are from C-horizon (parent material) only.
[3] Size fraction <32->2 mm.

thickness. The wide scatter of values ($r = 0.44$ in Fig. 8A, and 0.39 in Fig. 8B, both significant at the 95% confidence level) is attributable to stratification within the regolith, random concentrations of stones, and concentration of clay in soil **B horizon**.

In this study, dry bulk densities were determined for undisturbed regolith using a sand cone method described in Appendix 1. These values (Fig. 9) represent the entire soil including particles >2 mm. Particles >2 mm were not included in Beke's analysis. Again, there is a general increase in bulk density with depth ($r = 0.52$ at the 95%

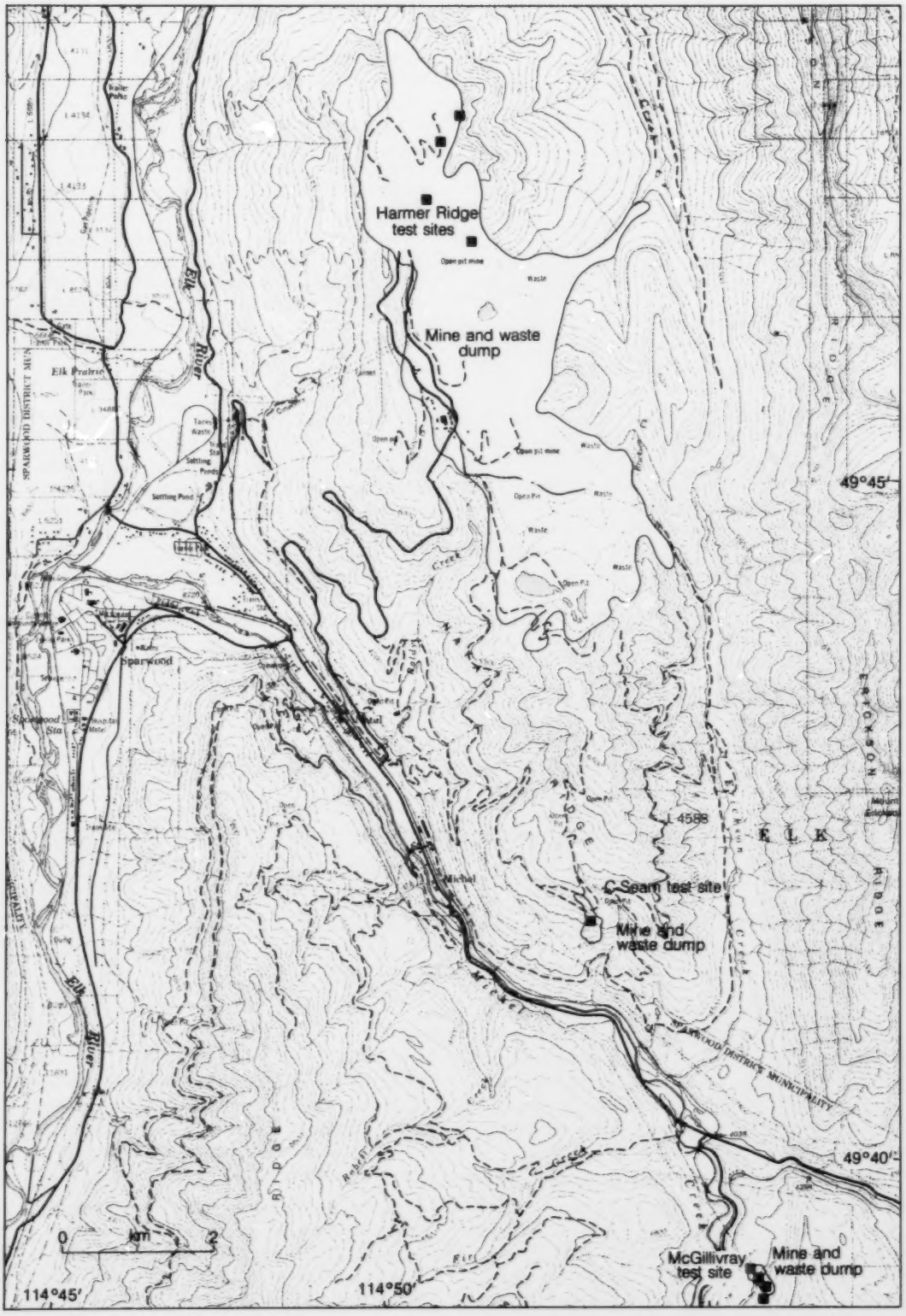


Figure 3A. Locations of the McGillivray, C-Seam, and Harmer Ridge test sites, Elk Valley, British Columbia.

confidence level). The scatter of values is attributable to the same factors as were mentioned previously in connection with Beke's data. The two data sets are not comparable because of the different methodologies used. For reasons stated in Appendix 1, I concluded that, of the two methods, the sand cone density method is superior, and chose to use it throughout this study.

Clay mineralogy

The clay mineralogy of surficial deposits at various locations in the Rocky Mountain Front Ranges and Foothills has been described by numerous authors, for example, Jackson (1977), Rutter (1972), and Kodama and Brydon (1966). The work of Beke (1969) has been the most thorough to date for soils overlying coal-bearing units within the Rocky Mountains and Foothills. He found kaolinite, illite, and "vermiculite-like clay that does not expand upon K-saturation" (p. 51) to be the dominant clay minerals in regolith of the Marmot Creek basin. He found smectite clays to be the dominant clay mineral in regolith of the Deer Creek basin. He noted that these clays were not pure smectites but contained interstratified clays which expand to 14 Å rather than 17 Å upon glycolation (exposure to an ethylene glycol atmosphere). These interstratified expandable clays were derived ultimately from the Upper Cretaceous shales beneath the Deer Creek basin (Kodama and Brydon, 1966).

Samples of regolith of both glacial till and colluvial origin were taken from coal-bearing areas throughout the Rocky Mountain Front Ranges and Foothills (Fig. 1) during this study. The clay mineralogy was determined by staff of the clay mineralogy laboratory of the Institute of Sedimentary and Petroleum Geology in Calgary under the direction of Dr. A.E. Foscolos; the methodology used is detailed in Appendix 2. Both whole sediment and clay size fraction (<2 μm) were studied. The results are summarized in Table 5.

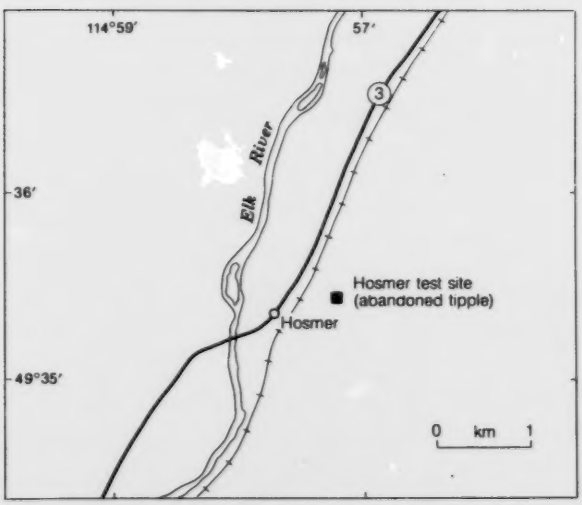


Figure 3B. Location of the Hosmer test site, Elk Valley, British Columbia.

Two assemblages of bedrock-influenced clay minerals are present in the regolith samples. Those samples taken from regolith derived from the "Coalspur Beds" or equivalent units (Coalspur, Obed Mountain) are dominated by smectite as described by Beke and Kodama and Brydon (Fig. 10A, B). This clay shows a characteristic expansion from ~15 Å at room (35-45%) relative humidity to ~17 Å upon glycolation and collapse to ~10 Å following heating to 550°C. Also present are randomly interstratified illite and vermiculite. The vermiculite rapidly rehydrates and

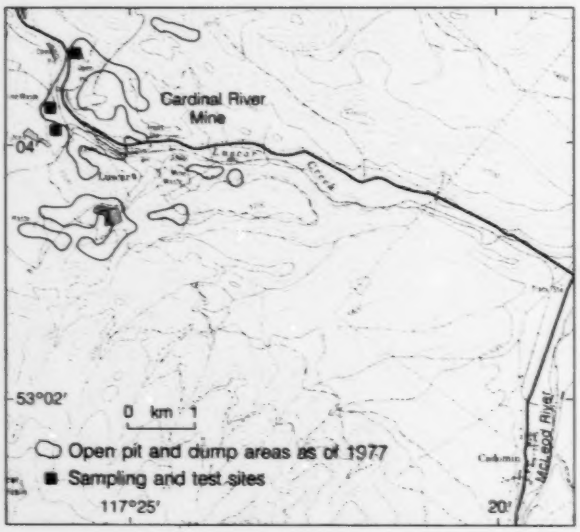


Figure 4. Locations of test sites at the Cardinal River Mine, Alberta (modified from Murray, 1977).

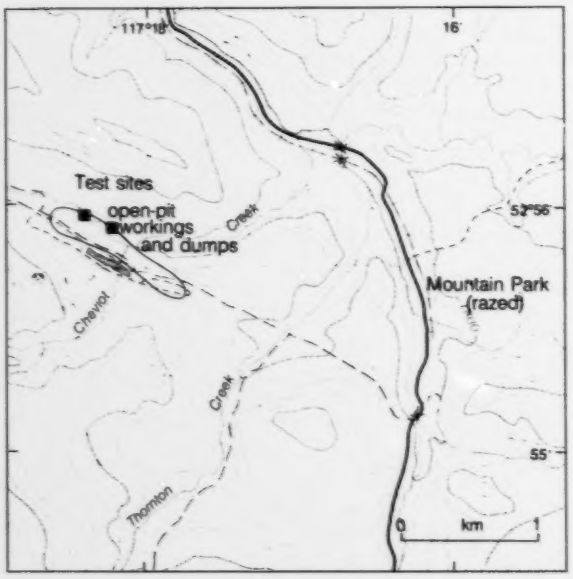


Figure 5. Locations of test sites at Mountain Park, Alberta.

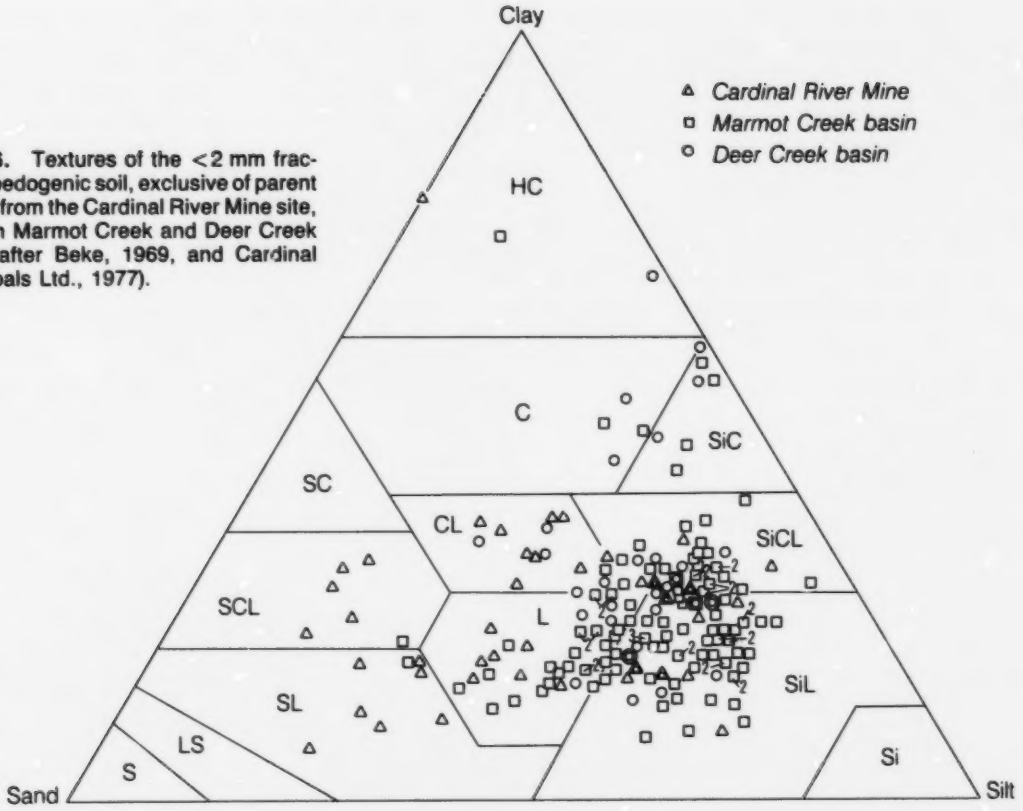


Figure 6. Textures of the <2 mm fractions of pedogenic soil, exclusive of parent material from the Cardinal River Mine site, and from Marmot Creek and Deer Creek basins (after Beke, 1969, and Cardinal River Coals Ltd., 1977).

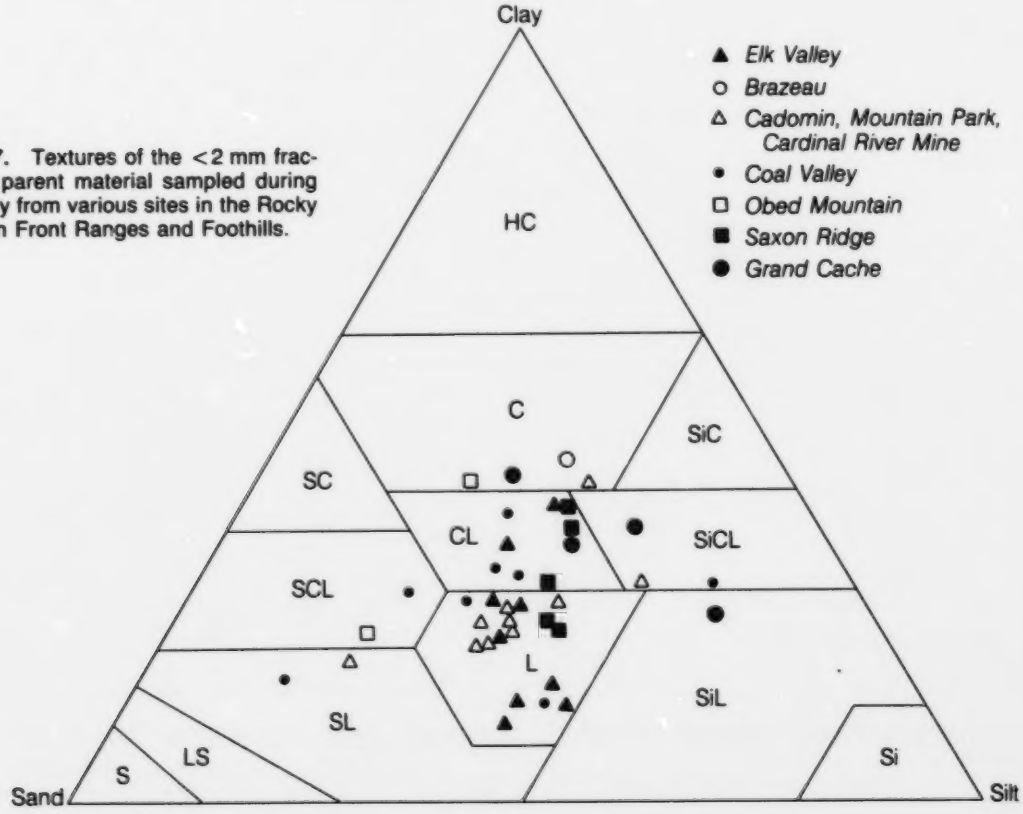


Figure 7. Textures of the <2 mm fractions of parent material sampled during this study from various sites in the Rocky Mountain Front Ranges and Foothills.

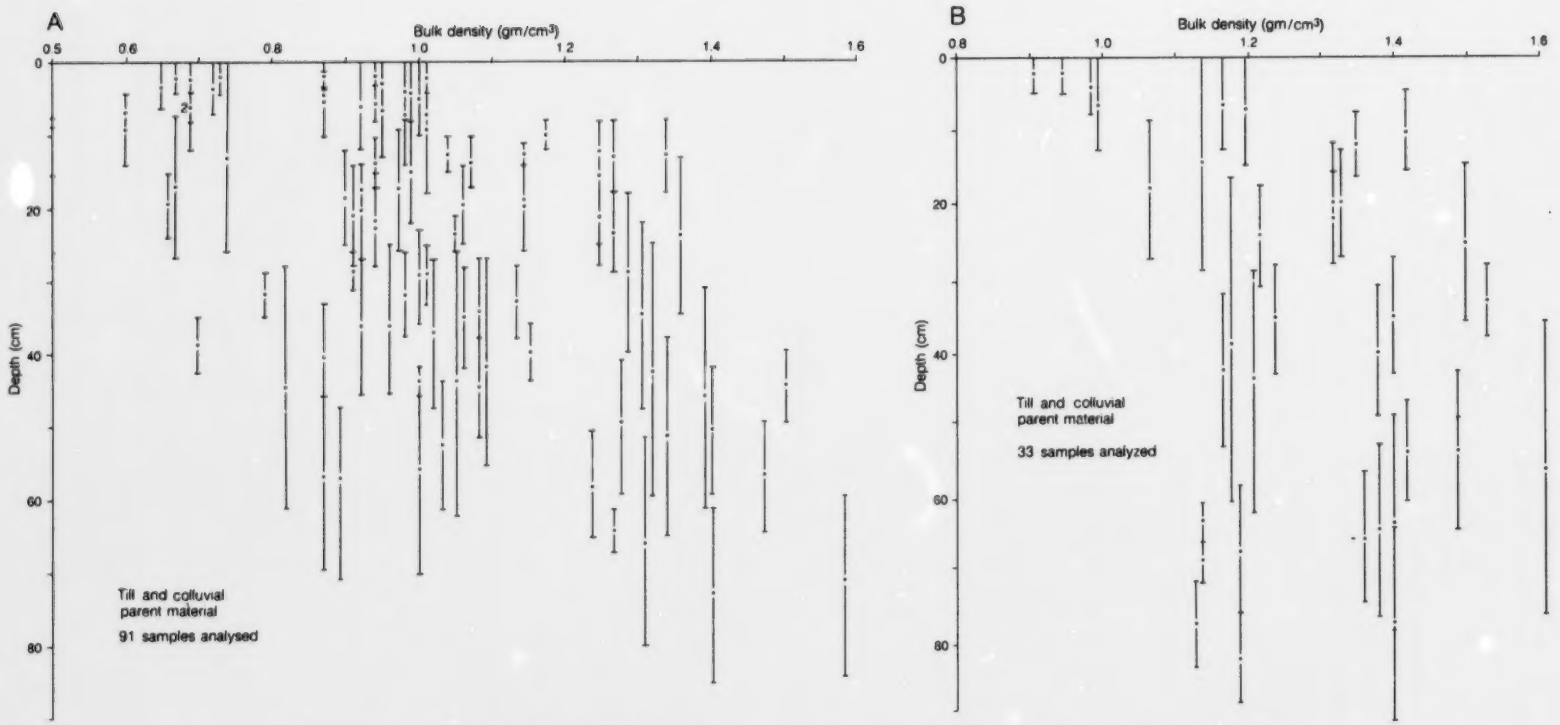


Figure 8. Plots of bulk density vs. depth for regolith in coal-bearing areas of the Rocky Mountain Front Ranges and Foothills exclusive of surface organic horizons: **A)** data from Beke (1969) for Marmot Creek Basin ($r = 0.44$ at the 95% confidence level); **B)** data from Beke (1969) for Deer Creek Basin ($r = 0.39$, significant at the 95% confidence level).

expands following heating to 550°C. That vermiculite is randomly interstratified with illite is indicated by a broad tail which forms on the 14 Å side of the 10 Å illite peak at room humidity following heating to 500°C (MacEwan et al., 1961; Fig. 10A, B). Vermiculite is further corroborated by its collapse to 10 Å upon treatment with KCl (compare the Ca and K treated samples at 1% relative humidity; see Fig. 10A, B). Kaolinite is present in all samples of "Coalspur Beds" regolith tested.

Samples from regolith overlying the Kootenay Group (Crowsnest Pass/Elk Valley), the Luscar Formation (Brazeau/Mountain Park/Cardinal River Mine/Grande Cache), and the Gething Formation (Saxon Ridge) comprise a second assemblage. The dominant clay mineral is a mixed-layered clay composed of random interstratifications of illite (listed as a separate mineral on Table 5), vermiculite, and smectite (Fig. 10C-H). Kaolinite is present as a separate mineral in all samples. Chlorite appears to be absent from Kootenay regolith but is present in most samples of Luscar and Gething regolith. Two samples from Luscar regolith had smectite as the dominant clay mineral (Table 5, samples 2077M1 and 2077M3). These samples probably reflect the local influence of sodic shales which are occasionally encountered in the Luscar Formation (Devenny and Ryder, 1977).

A variety of tests are required to identify the mixed-layered components present (Fig. 10C-H). As previously stated, vermiculite is confirmed by its collapse to 10 Å following treatment with KCl. The addition of potassium essentially alters the structure of vermiculite to that of illite.

Table 5. Semi-quantitative mineralogy of regolith, Rock Mountain Front Ranges and Foothills

Site	Sample no.[1]	Whole soil (< 4 mm)[2,3]			Clay (< 2 µm)[2,3]		
		Major	Minor	Trace	Major	Minor	Trace
Crowsnest Pass/Elk Valley, Alta./B.C.	2567C1	Q, F	I, ML	K	Q, I, ML	K	—
	2567C3	Q, C, D	I, ML, F	K	C, Q, I, ML	K	—
	2667C2	Q	I, ML, K, D, C, F	—	Q, I, ML, K	—	D, C
	8677E4	Q, K	I, ML	—	Q, K, I, ML	—	—
	8677E5	Q, C, D	K, I, ML	F	Q, I, ML	C, K	—
Nordegg, Alta.	1977S5	Q	C, D, K, I, ML	—	Q, K, I, ML	—	—
	1977S10	Q, C, D	I, ML, K, F	—	Q, K, I, ML	C	D
Mountain Park/ Cadomin/Luscar, Alta.	1477M1	Q, Mo, I, ML, F	K	—	Q, K, Mo, I, ML	—	—
	1477M6	Q, I, ML	K, Chl	—	Q, K, I, ML	F	Chl
	2077M1	Mo, I, ML, Q, K	F	—	Q, K, ML	—	F, Chl
	2077M3	Q, F, M	Chl, I, ML	—	Q, Chl, K, I, ML	—	—
	2077M9	Q, I, ML, D, Q	K, Chl	—	Q, K, I, ML	Chl	—
	2177M2	Q, K	—	—	Q, K, I, ML	—	—
	2177M3	Q, F, D, K	C, I, ML	—	Q, K, I, ML	—	—
	2177M4	Q, F	I, ML	Chl, K	Q, K, Chl, I, ML	—	F
	2177M5	Q, F, I, ML	K, Chl	—	Q, K, Chl, I, ML	—	—
	2177M6	Q, C, I, ML	F	K	C, Q, I, ML	K	—
	2177M8	D, C, Q, I, ML	Chl, K	—	Q, K, Chl, I, ML	—	—
	2177M9	Q, D, C, I, ML	K	P, F	Q, K, I, ML	—	D, C
	2177M10	Q, F, D, I, ML, C	—	Chl, K	Q, K, Chl, I, Ml	—	—
	1687M1	Q, I, ML, D	F, C, K	—	Q, K, I, ML, Mo	—	—
	1687M2	Q, C, D	I, ML, K	—	Q, K, I, ML	—	D, F
Grande Cache, Alta.	1087S1	Q, F, C, D, ML, I	K, Chl	—	Q, Chl, K, I, ML	—	F
	1087S2	Q, I, ML, K	F	D	Q, K, I, ML	—	—
	1087S3	Q, I, ML, K	F	—	Q, K, I, ML	—	—
Saxon Ridge, B.C.	1287N1	Q, I, ML	F	—	Q, K, I, ML	—	—
	1287N3	Q, C, D, I, ML, K	—	Chl	Q, K, I, ML	—	C, D
	1287N4	Q, K, I, ML	F	—	Q, K, I, ML	—	—
	1387N1	Q, C, D, I, ML	F	K, Chl	Q, K, I, ML	C, D	—
Coalspur, Alta.	1377L4	Mo, Q, F, I, ML	—	—	Mo, K, Q, I, ML	—	—
	1377E1	Mo, Q, F, K, I, ML	—	—	Mo, K, I, ML	—	—
Obed Mountain, Alta.	2277A4	Mo, Q, F, I, Ml	—	—	Mo, Q	K, I, ML	—
	2277A7	Mo, Q, F, I, ML	—	—	Mo, Q	I, ML	

[1] Samples taken from both till and colluvium below the soil.
[2] Abundance estimates: major >5%; minor 2-5%; trace <2%.
[3] Mineral abbreviations: C — Calcite; Chl — chlorite; D — dolomite; F — feldspar; I — illite; K — kaolinite; ML — mixed layered vermiculite and smectite; Mo — smectite; P — pyrite; Q — quartz.

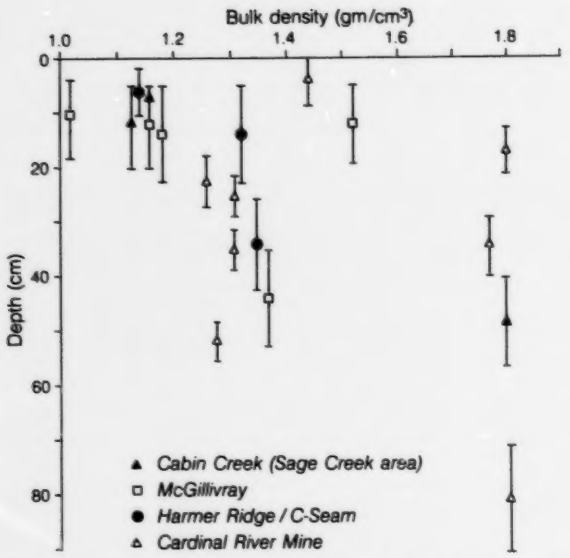


Figure 9. In-situ soil density plotted against depth for natural soils tested using a sand cone method (r = 0.52 at the 95% confidence level).

Vermiculite and illite appear to be present in about equal quantities based upon relative peak shapes (MacEwan et al., 1961). Smectite is confirmed by an apparent collapse of a 15 Å peak at room humidity back to 10 Å upon the glycolation of the CaCl • $2H_2O$ treated sample. This apparent collapse is actually the progressive disappearance of the smectite 001 peak as it shifts from 15 Å to 17.5 Å as seen in Figure 10H. This disappearance occurs for random mixed layers of illite and smectite (montmorillonite) with ratios from about 8:2 to 7:3 respectively (MacEwan et al., 1961). The presence of smectite is further confirmed by its permanent collapse to ~10 Å following heating to 550°C and its expansion with increasing humidity and glycolation despite treatment with KCl.

Quartz is ubiquitous in all samples. Feldspar, calcite, and dolomite are major or minor components in whole sediment and/or clay (<2 μm) fractions in many samples.

Soil chemistry

Regolith contains nutrients (both organic and inorganic) that are essential to the growth of plants. The levels of nutrients naturally available in soil and parent material components of regolith and the degree to which soil and parent material are able to retain nutrients or supply them to growing plants (as indicated by water-soluble and exchangeable cations and anions) are determined by several variables.

Texture. The nutrients available for exchange are primarily present in the clay size (<2 μm) fraction. The fineness of clay size particles provides clays with an extremely large surface area for ion adsorption relative to larger particles. Consequently, soil with a large content of organic or inorganic clays will have a larger capacity to exchange cations than soils with overall coarser textures, all other factors being equal.

Degree of leaching. Soil components of regolith that have been significantly leached have typically lower contents of exchangeable cations, lower pH values, and lower base saturations than comparable less-leached soils. Podzols and, to a lesser extent, Luvisols should be expected to be more acidic and have smaller contents of available nutrients than other soils. These soils form under deciduous, mixed, and coniferous forest. These plant assemblages predominate over many prospective or active mine sites.

Clay mineralogy. The degree to which clays can adsorb and exchange cations and anions is determined by the molecular structure of clay minerals, the presence of other ions substituting for silicon or aluminum or occupying interlayer positions within the lattice and the ability or inability of the lattice sheets to expand and incorporate water or exchangeable cations and anions. For example, values summarized by Birkeland (1974, p. 86) indicate that the ionic exchange capacity of kaolinite, which is nonexpanding, is in the range of 5 to 50 times less than the ranges of values for the expanding clay minerals smectite (montmorillonite) and vermiculite. Consequently, regolith rich in these latter clay minerals should have higher exchange capacities than soils rich in kaolinite.

Analytical methods. In soil chemistry, values may differ with the analytical methods used to obtain them. For example, if ammonium acetate is used as an **extracting reagent** on a soil containing vermiculite, the ammonium ion will collapse the margins of the clay lattice trapping exchangeable ions in interlayer positions (Fig. 11) and producing an anomalously low cation exchange capacity (Barshad, 1948). Calcite and dolomite will contribute dissolved calcium and magnesium to the exchange reagent and will produce anomalously large values for exchangeable calcium and magnesium unless analytical precautions are taken. These problems are discussed in Appendices 3 and 4.

Data presented by Beke (1969) and Cardinal River Coals Ltd. (1977 unpublished) have shown that the mineral and organic soil horizons in the respective study areas are predominantly acidic with a significant **exchange acidity**. The range of values for parent material **total organic carbon**, carbon-to-nitrogen ratio, and total cation exchange capacity is similar to that of the overlying soil. Both are uniformly nutrient-poor. Virtually all soluble salts have been removed.

Sampling during this study was confined to the volumetrically more significant parent material fraction of regolith (Fig. 12, 13). Values of water-soluble cations anions and pH values fall within the same range as those already reported, i.e., soluble salts have been leached from the sampled regolith and the levels of nutrients such as P and N are extremely low. Values for extractable cations cannot be compared with values determined in previous studies because methodologies differed (Appendices 3 and 4).

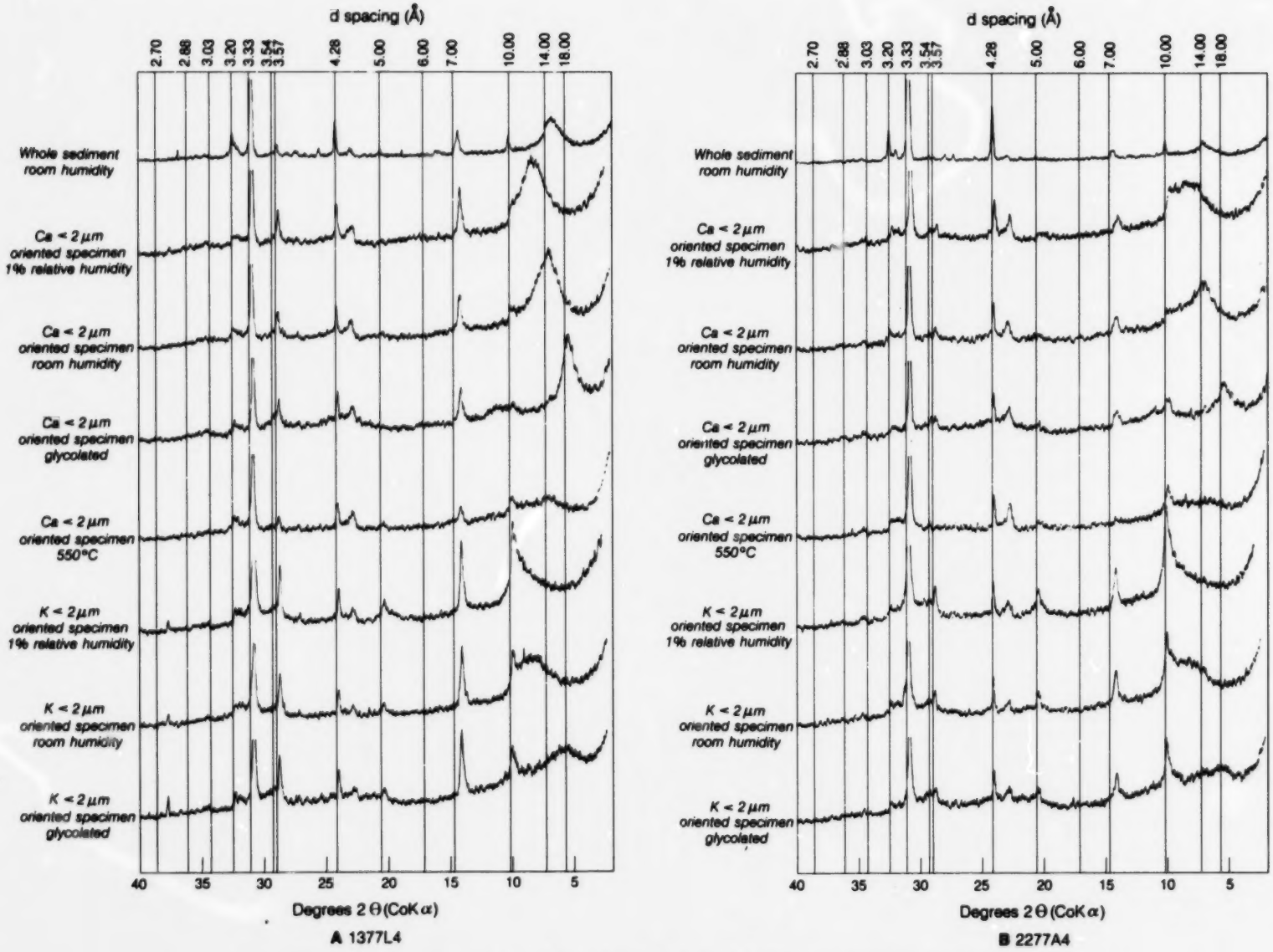
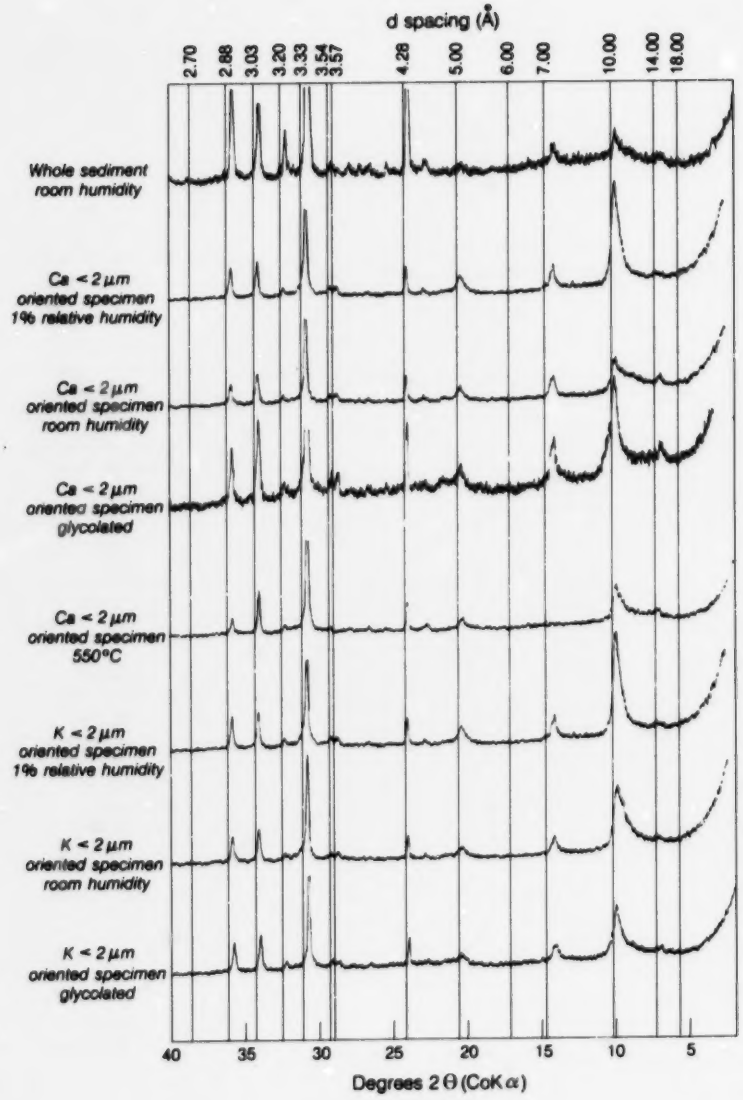


Figure 10. X-ray diffractograms of whole sediment and clay size fractions of regolith from coal-bearing areas of the Rocky Mountain Front Ranges and Foothills using a cobalt-potassium X-ray source: **A)** 1377L4; **B)** 2277A4; **C)** 1977S1; **D)** 867E2; **E)** 2077M1; **F)** 1087S1; **G)** 1287N4; **H)** 1687M2.



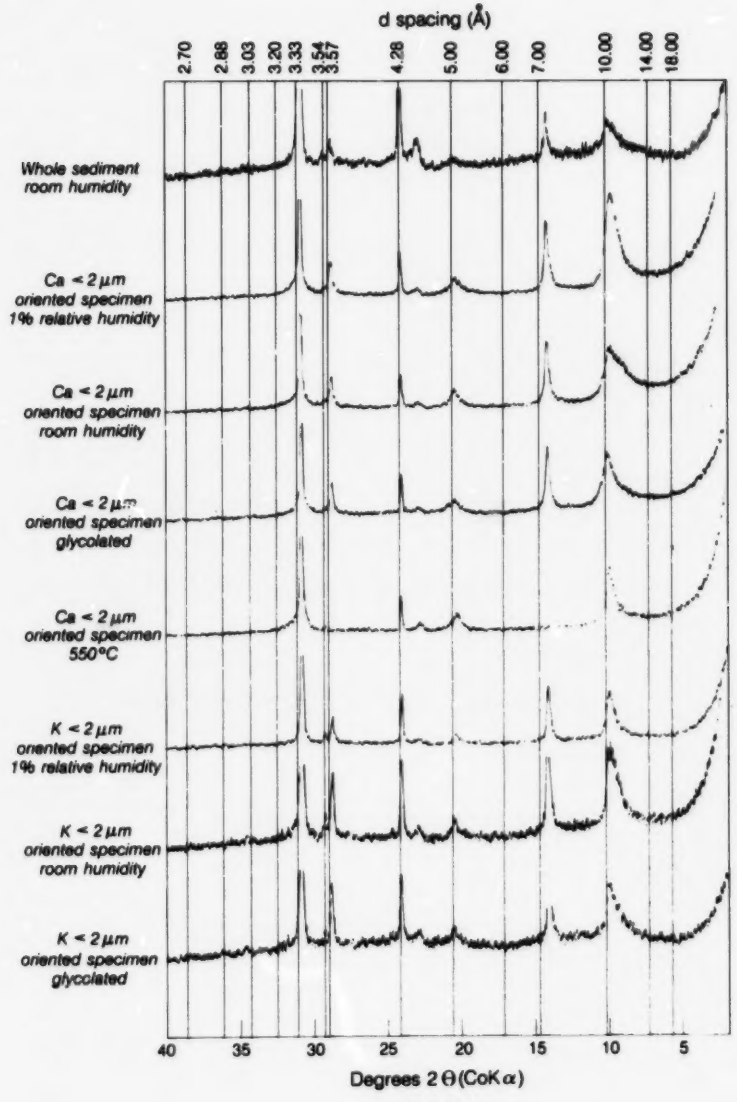
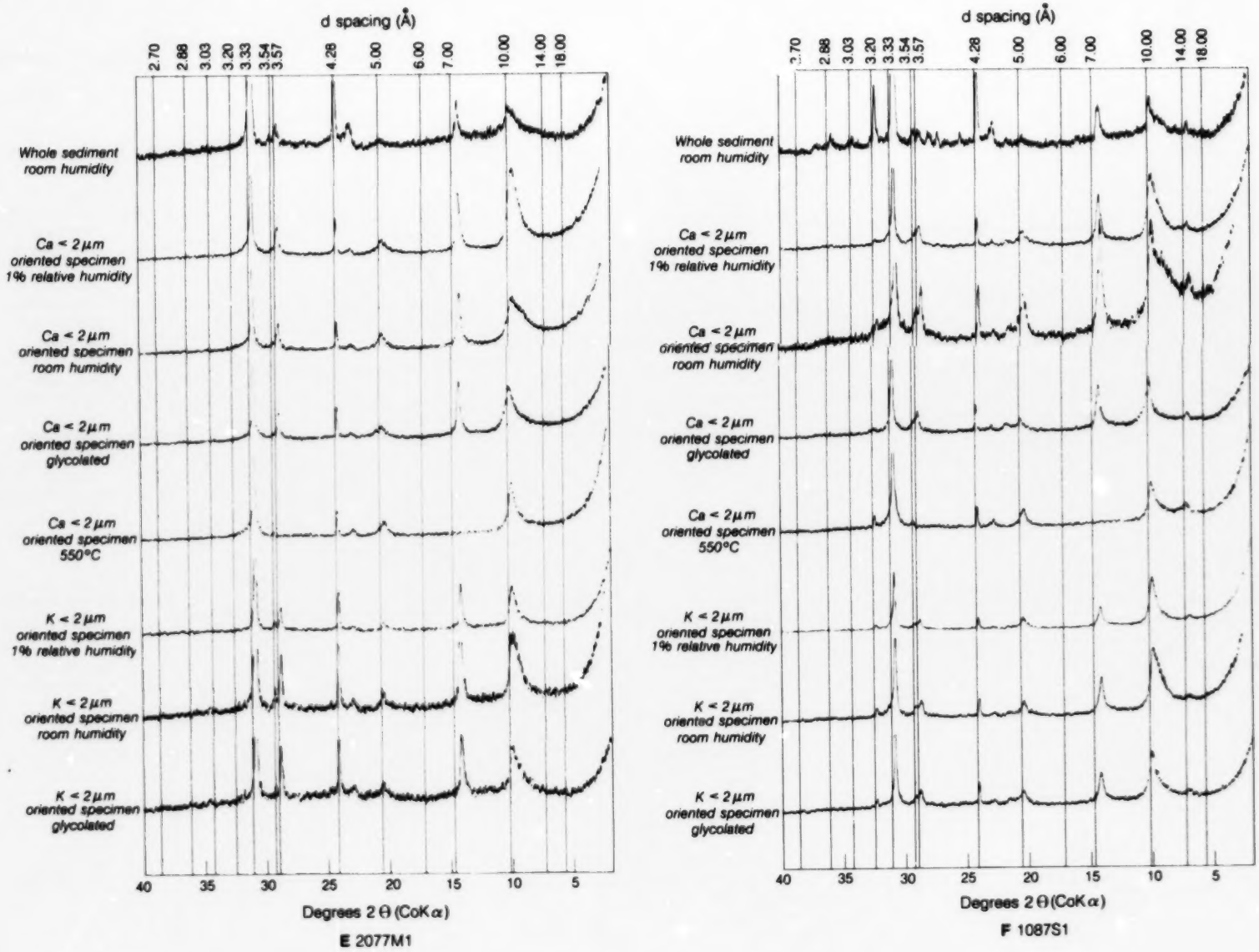


Figure 10 (cont.)



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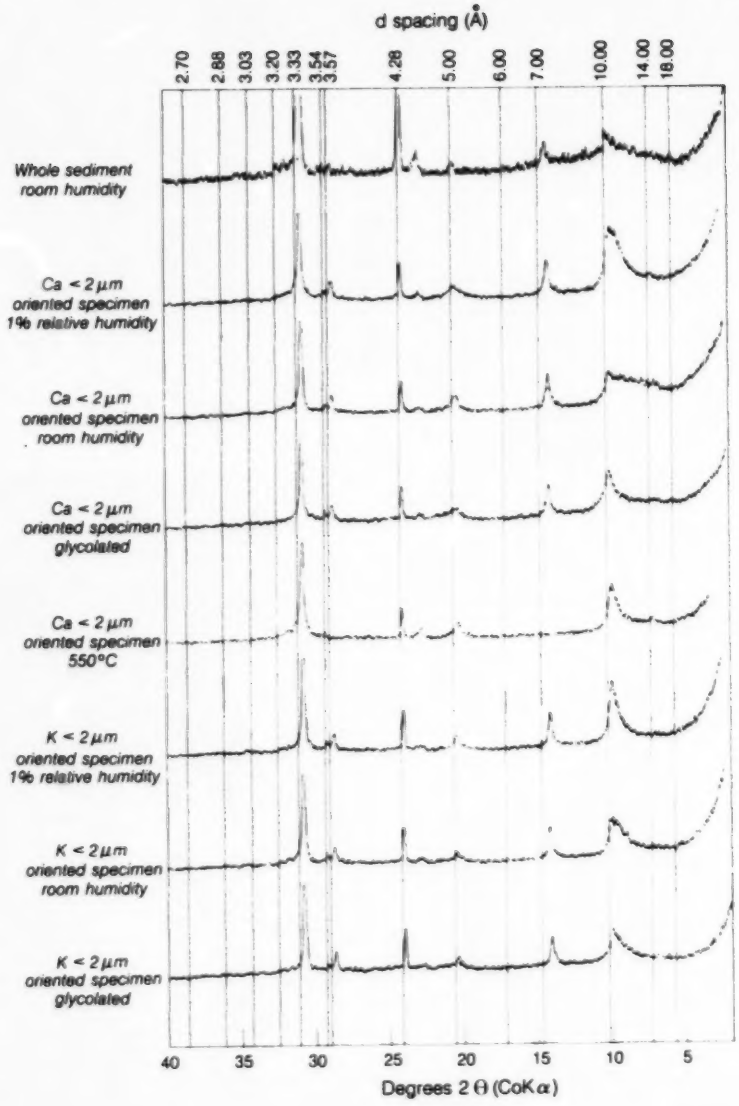
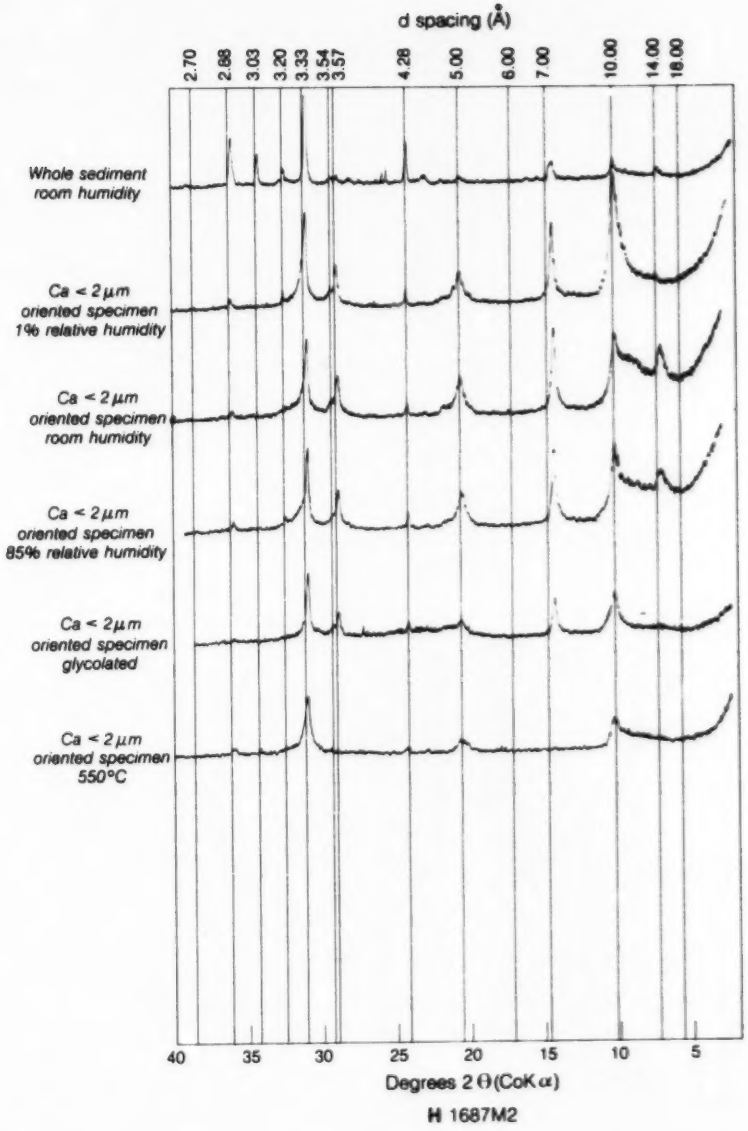


G 1287N4



H 1687M2

Figure 10 (cont.)

ROCK WASTE

Open-pit mining requires that noncoal-bearing rocks separating coal seams from the surface be removed and discarded in a dump (Fig. 14). The dumping process results in a heterogeneous mixture of fragmented rock material ranging from sandstone and conglomerate to coal and coaly shale. Because the terrain is steep where mining is commonly carried out, the soils and regolith are sometimes too thin to salvage. Consequently, the rock waste itself must be reclaimed.

This section examines the textural, mineralogical, chemical, and physical properties of rock waste. These properties are compared to, and contrasted with, those of regolith.

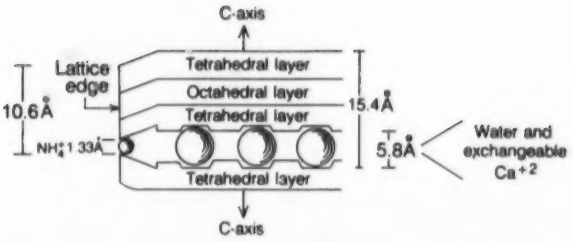


Figure 11. Schematic diagram depicting the "pinching" effect of an ammonium ion on the edge of the vermiculite lattice which prevents the escape of exchangeable cations - in this case Ca^{+2}.

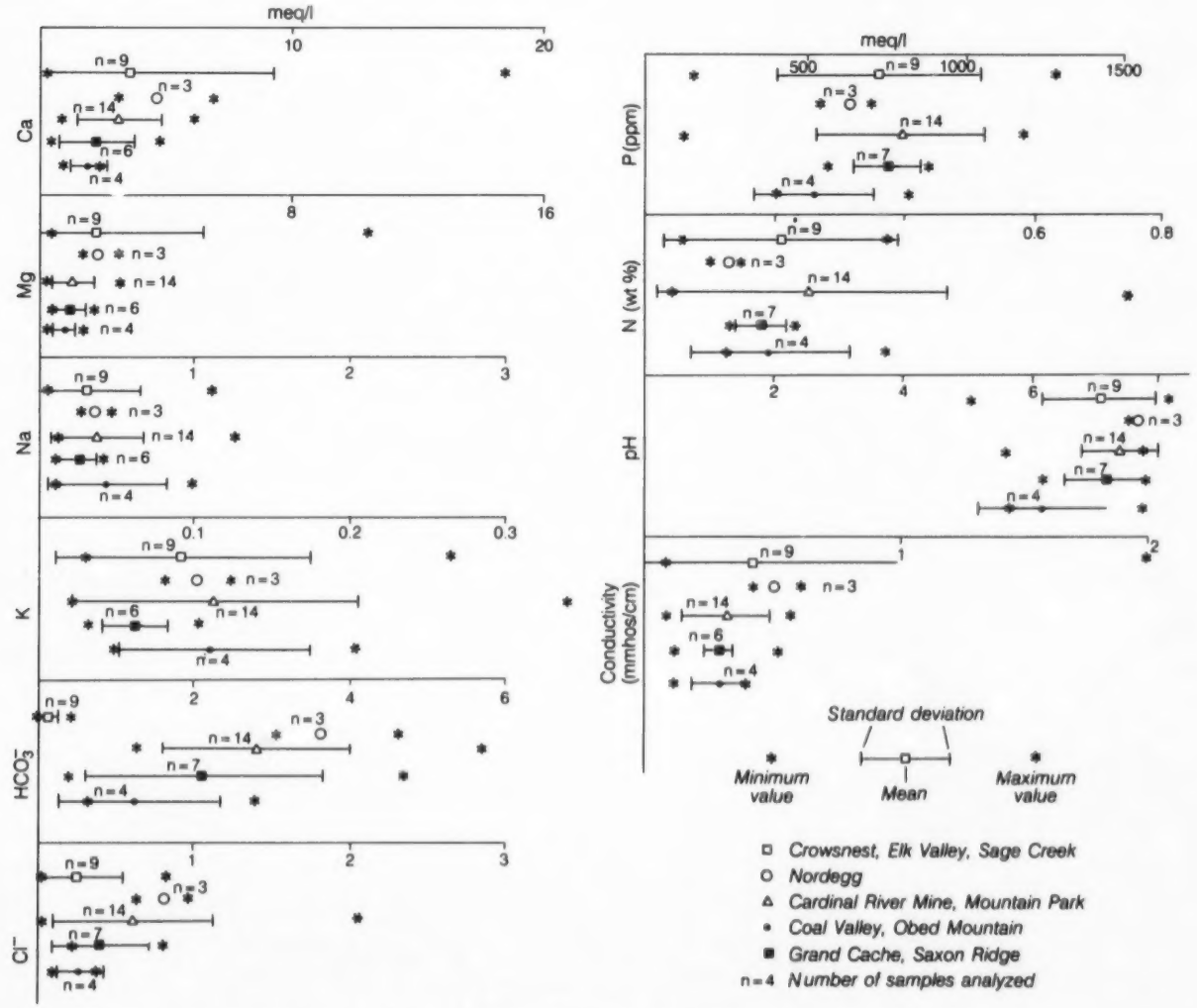


Figure 12. Water-soluble cations and anions for samples of regolith from coal-bearing areas, Rocky Mountain Front Ranges and Foothills.

Texture

The rock waste produced by the open-pit mining operation is typically a coarse, poorly sorted sediment with a varying content of coal or carbonaceous shale in the fine fraction. Table 6 summarizes data collected during this study and that of McCoy (1975). Coarse fraction sampling during this study only included the <32 mm to >2 mm size interval because of the difficulty of transporting larger samples required to represent accurately the content of clasts $\geqslant 32$ mm. Samples were obtained from depths below -5 cm to avoid the coarse, wind-winnowed surface lag (Root, 1976). Comparison of data collected for this study (Tables 4 and 6) indicates that the mean weight percent for the <32 to >2 mm fraction of rock waste falls within the same range as that of natural regolith found on coal-bearing sites. Comparison with Beke's (1969) data indicates rock wastes to be stonier by a factor of 2 or 3. However, no upper limit of grain size was specified for Beke's data. McCoy (1975) used sampling intervals of <19 to >2 mm and >19 mm at Tent

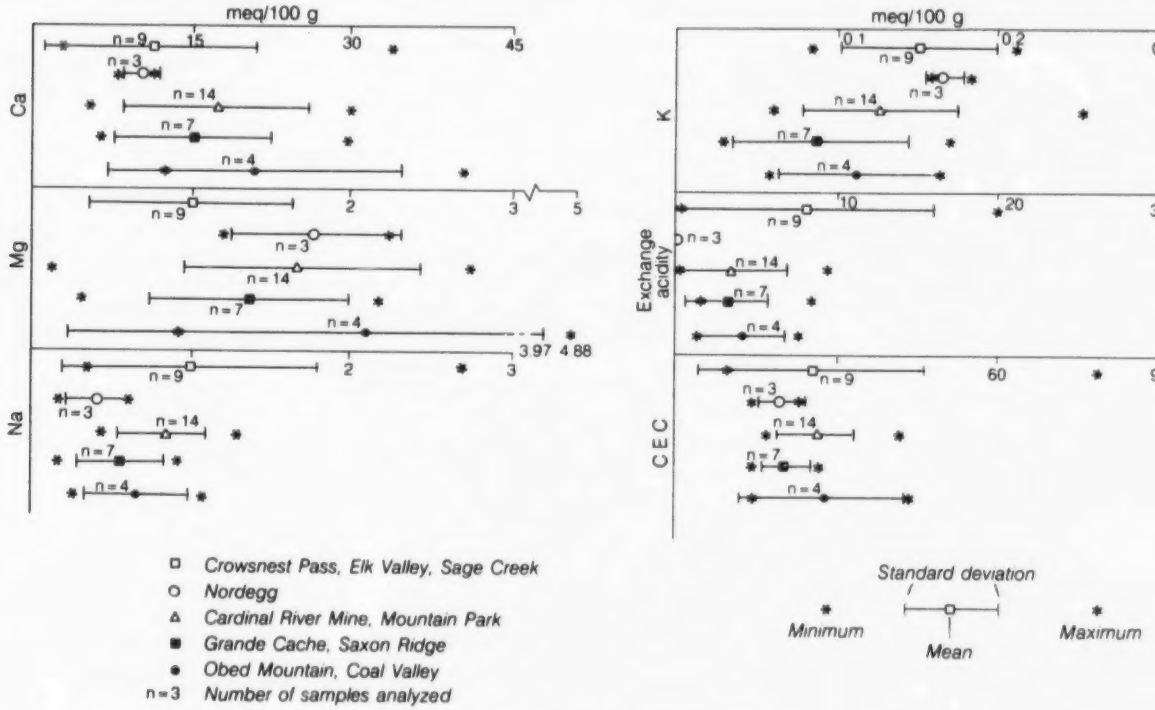


Figure 13. LiOAc-extractable cations and cation exchange capacities for samples of regolith from coal-bearing areas, Rocky Mountain Front Ranges and Foothills.

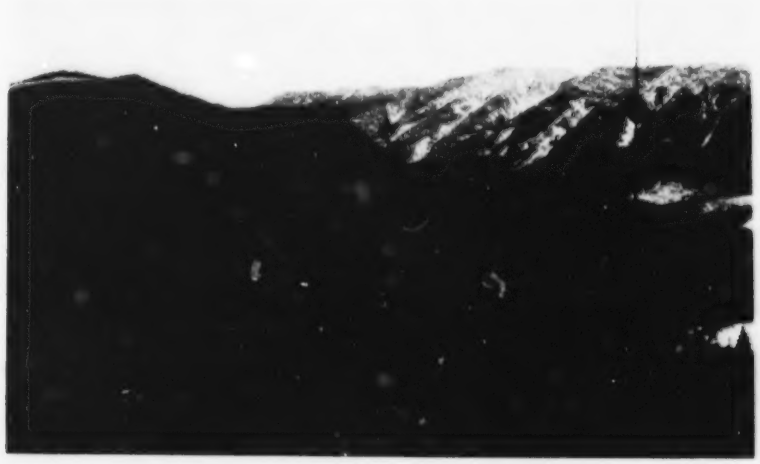


Figure 14. A large rock waste dump at Harmer Ridge, B.C. Vertical relief is about 450 m. (ISPG 2033-3)

Mountain. Although not directly comparable with data collected during this study because different size intervals were measured, his data indicate rock wastes to contain a larger >2 mm fraction than does regolith found in coal-bearing areas.

Sand, silt, and clay contents of rock waste samples are plotted in Figure 15. Rock waste contains more sand-size fragments in its fine fraction (<2 mm) than does regolith. Furthermore, because hydrometer analysis was used to determine texture, the lower settling velocity of carbonaceous particles in the <2 mm fraction under-represents sand and over-represents silt and clay in proportion to their content (Table 7).

Past studies of coal mine rock waste have speculated upon or noted a progressive breakdown of coarse clasts with time (Root, 1976; Devenny and Ryder, 1977). Rapid breakdown of shales and some sandstones (Fig. 16) was noted in all areas studied. Freeze-thaw and wet-dry cycles have been implicated in the physical breakdown of argillaceous rocks (Hudec, 1978, p. 5; Mugridge and Young, 1983). Thus, a progressive decrease in the <2 mm fraction should be observed with depth. Rock waste was sampled to determine if this disintegration was supplying any sediment to the chemically active <64 μm fraction. Textural samples were taken at successive 10-20 cm depth intervals starting at -5 cm. Sampling was continued until clasts larger than the sampling interval were encountered. Consequently, most sampling was stopped at depths less than 30-50 cm. Sampling at 5 cm intervals, as originally intended, proved to be impractical because clasts with dimensions greater than 5 cm were often encountered.

Figure 17 presents data from sites at McGillivray, Hosmer, and Mountain Park. The sampling interval depth is plotted against the ratio of the weight of clay and silt over the weight of the total sample finer than 32 mm. The McGillvray Mine was regraded and seeded in 1973. The upper 10 cm is actually coarser than the samples examined from below 10 cm. Wind winnowing of the surface, which has been previously described by Root (1976), results in a thin coarse lag at the surface, which has apparently been a factor at this site. The Hosmer Site is a former mine-mouth dump which was abandoned during World War I. Carbon content of this material usually exceed 25% by weight. After more than 60 years, the samples show no indication of added silt and clay size fines. The Mountain Park North Pit Mine dump, which has been inactive since about 1952, also yielded negative results. Similar negative results were obtained from sites reclaimed during the 10 years prior to sampling in 1978, at Mountain Park North Pit, Harmer Ridge, and Cardinal River Mine.

In conclusion, no significant breakdown of rock waste to silt and clay size particles (<64 μm) appears to have occurred over periods of up to 60 years within rock waste at the sites investigated. Although coarse particles do breakdown to form finer ones as described by Root (1976) and, as shown in Figure 16, these fragments are coarser than 64 μm.

Table 6. Coarse fraction particles in rock waste

Study	Site[1]	Weight % X	s	Max.	Min.	n
Size fraction <32->2 mm						
This study	MG	43	15.9	89	20	8
	H	42	16.5	72	19	19
	CR	25	12.1	50	10	12
	MP	27	12.5	57	7	24
Size fraction >19 mm						
McCoy (1975)	TM	28	9.9	44	6	12
Size fraction <19->2						
McCoy (1975)	TM	50	11.4	64	69	12

[1] MG – McGillivray; H – Harmer Ridge; CR – Cardinal River Mine; MP – Mountain Park; TM – Tent Mountain.

Table 7. Carbon contents of <2 mm fractions from selected open-pit coal mine rock wastes, Rocky Mountains, Alberta and British Columbia[1]

Site	n	Weight % Mean	Max.	Min.	δ
MacGillivary	20	14.42	29.18	1.93	8.24
Harmer Ridge/C-Seam	15	6.87	27.82	1.77	6.68
Cardinal River Mine	7	4.70	7.53	2.27	1.80
Mountain Park	18	19.02	78.46	2.32	17.48

[1] Values were determined by proximate analysis. Error ranges from ±0.1% for samples in the 0-5 wt. % range to ±5% in the >20 wt. % range.

Bulk density

Harrison (1974b) previously measured in-place bulk densities of rock wastes from both **platform** sites and **free faces** of dumps. He found that, depending upon compaction and content of carbonaceous shale and coal, these values ranged from 1.43 g/cm$_3$ to 0.80 g/cm^3. Direct comparison of these values with those of regolith would be misleading. The significant contents of carbonaceous shale and coal with low specific gravities present in the rock wastes result in rock wastes and regolith having the same void ratios[1] at significantly different bulk densities. A sample of rock wastes with an in-situ bulk density of 1.45 g/cm^3 and a specific gravity of 2.0 has a bulk density equivalent to that of 1.91 g/cm^3 in natural soil with a specific gravity of 2.60 for its soil particles.

[1] The void ratio is the volume of void space divided by the volume of solids in a sediment.

Bulk density measurements (Fig. 18) were made at both reclaimed and unreclaimed mine sites, i.e., McGillivray, Harmer Ridge/C-Seam, Hosmer, Cardinal River Mine, and Mountain Park. This plot indicates a random variation between bulk density and depth for all samples. A similar random relationship is seen if the data are plotted site by site. An envelope encompassing bulk density values for regolith samples above 55 cm taken from Figure 9 is plotted on Figure 18 for comparison. No apparent difference appears to exist between the two data sets. However, if differences in specific gravities of the two materials are taken into consideration, quite different results are obtained.

Specific gravity measurements were determined on the <32 to >2 mm and <2 mm fractions for bulk density samples of both rock waste and regolith. The weight percent content of each fraction was also determined and a mean specific gravity was computed for each sample of soil and rock waste. Void ratios were determined for both regolith

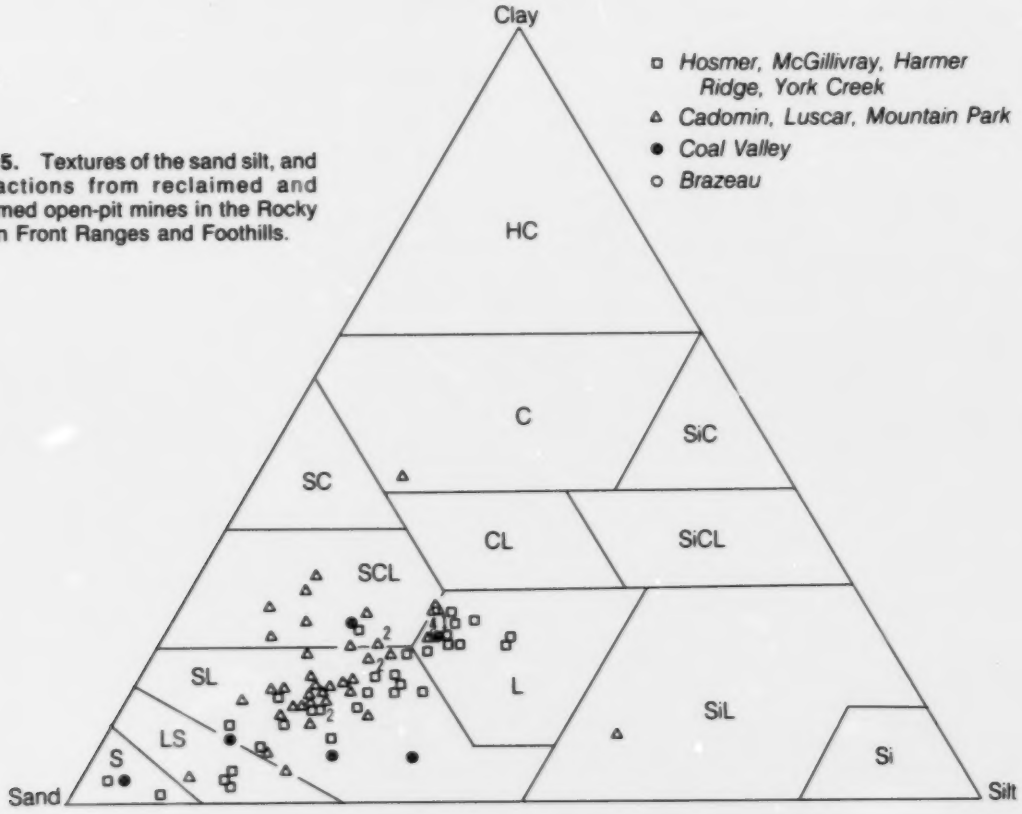


Figure 15. Textures of the sand silt, and clay fractions from reclaimed and unreclaimed open-pit mines in the Rocky Mountain Front Ranges and Foothills.

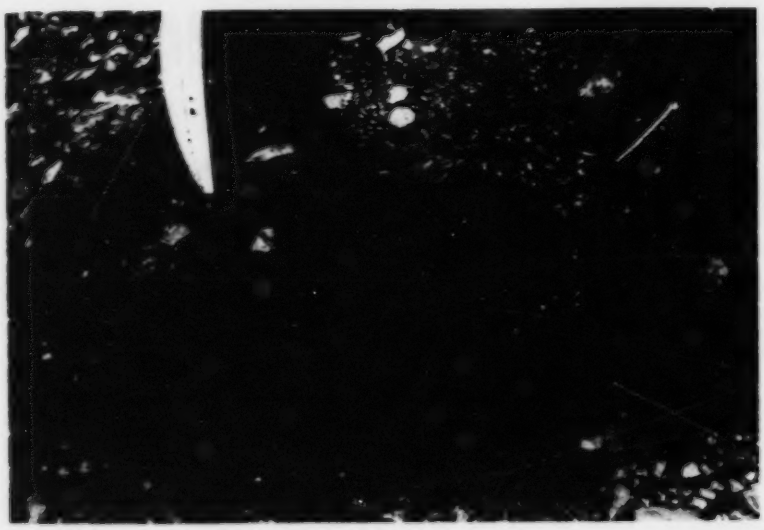


Figure 16. Physical disintegration of a block of shale exposed to the atmosphere for about 25 years at the Brazeau Colliery near Nordegg, Alberta. (ISPG 2033-5)

and rock waste data (Fig. 19). Although natural regolith and rock waste values overlap, void ratios for natural regolith are generally greater, i.e., it has a greater volume of void spaces, than those of rock wastes at similar depths. This finding is confirmed by using analysis of variants (ANOVA), at the 95% confidence level.

No data exist to document the initial bulk densities for rock wastes at any of the sites studied. However, similarity in the ranges of values between sites reclaimed or abandoned from 10 to 60 years prior to sampling suggests that the rock wastes at these sites are at, or close to, their original bulk densities. If this is so, no significant increase in the void ratio of rock wastes, i.e., no significant decrease in rock waste density, can be expected for periods of at least 60 years.

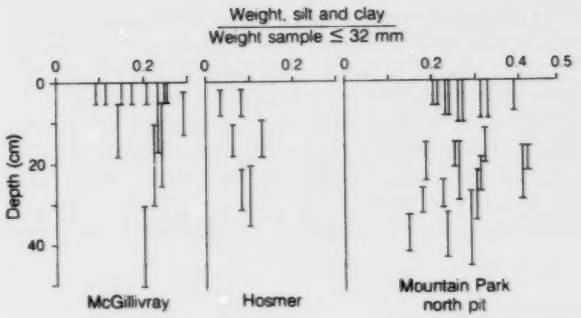


Figure 17. Quotient of total silt and clay weight and total sample weight plotted against sample depth for three waste dump sites of varying ages.

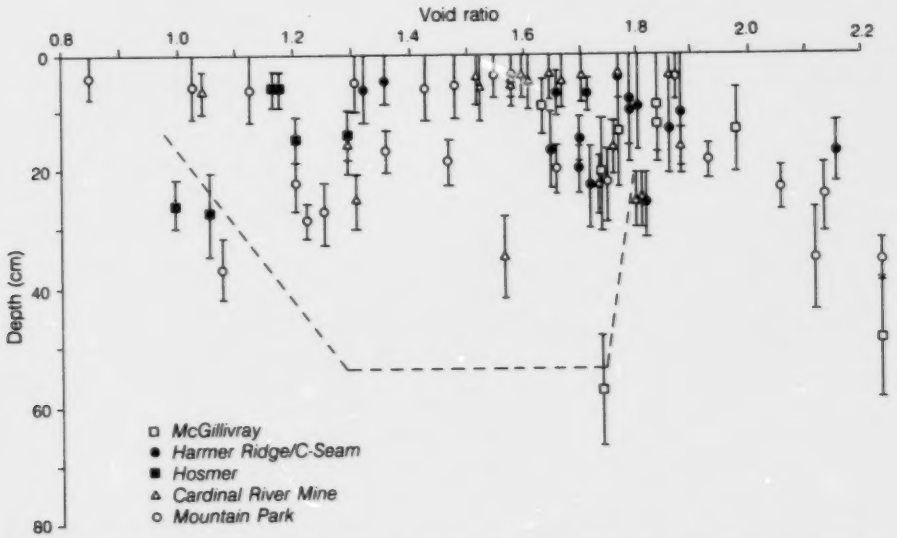


Figure 18. Bulk density vs. depth for rock waste samples from reclaimed and unreclaimed dump sites of widely differing ages. The dashed line indicates the limit of bulk density values for natural regolith above 55 cm depth as shown in Figure 9.

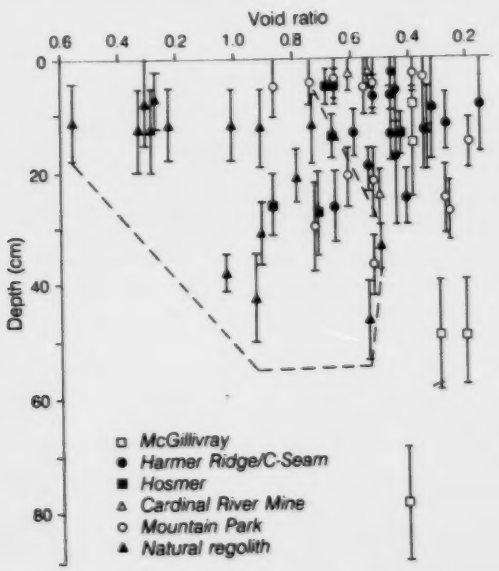


Figure 19. Void ratio vs. depth for the same rock waste samples plotted in Figure 18. The dashed line indicates the limit of void ratio values determined for natural regolith samples above 55 cm depth as shown in Figure 9.

Bulk density measurements and void ratio calculations were made for mixtures of rock waste and regolith and compacted regolith found around the margins of the McGillivray, Lower C-Seam, and at the Cardinal River Mine site. These mixtures were created inadvertently during mining activity. No statistically significant decrease in bulk density or increase in void ratios with progressive proximity to the surface was noted for these mixtures. Because up to 10 years had elapsed since reclamation at these sites, no assumptions with respect to initial bulk densities could be made as was the case for rock waste. However, no statistical difference was found between the void ratio values for rock waste plotted in Figure 9 and values determined on 19 samples of reworked regolith and mixed regolith and rock waste. It appears that progressive decrease in bulk density with proximity to the surface, as is characteristic of natural regolith, will require long periods to develop in reclaimed mixtures of regolith and rock waste.

Chemical properties

All three major coal-producing formations of the Rocky Mountain Front Ranges and Foothills (the Kootenay Group, Luscar Formation, and Coalspur Beds) are low in sulphur. Carbonate minerals are present as cements in these units. Consequently, they are predominantly alkaline. Acidic beds are usually only slightly acidic (pH 6.0 or higher). Locally significant sources of sodium are present in the Luscar Formation and Coalspur Beds but are absent from the Kootenay Group (Jackson, 1982). Values for soluble cation and anion concentrations from saturated paste extracts obtained from rock wastes from the Kootenay Group (Crowsnest Pass) and Luscar Formation (Mountain Park and Cardinal River Mine) are plotted in Figure 20, along with mean values for the same characteristics from the regolith data in Figure 12. No samples were collected for the Coalspur Beds. However, samples were obtained from

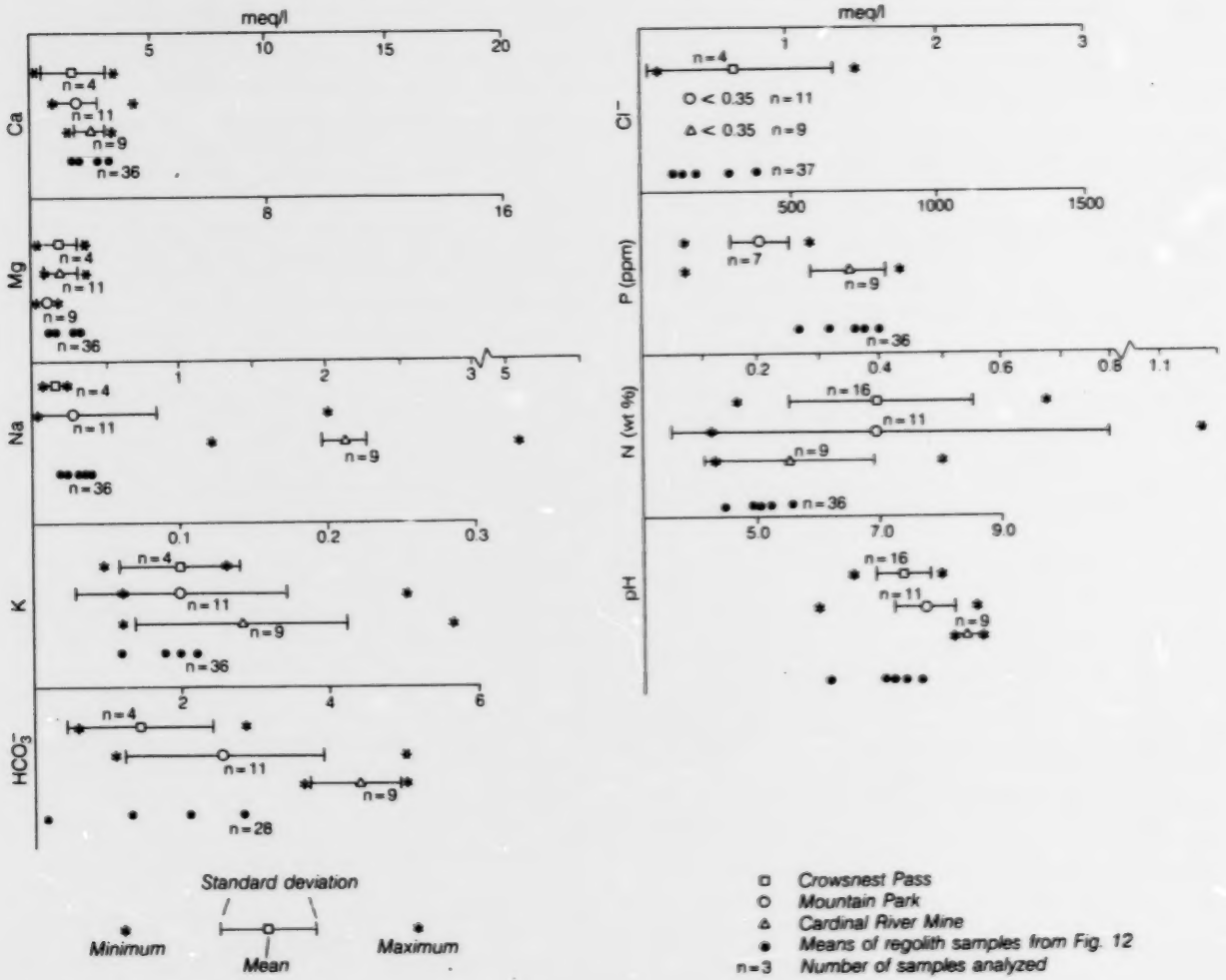


Figure 20. Soluble cations and anions measured from saturated paste extracts of rock waste samples.

cores taken from this unit as a part of an environmental impact study (Luscar-Sterco Ltd., unpublished data). Analyses of these samples yielded values that fall within the same ranges as those from the Luscar Formation. The only exception is sodium which is locally high because of the presence of sodic, smectite-rich shales. Values as high as 22.4 mg/L were recorded and no values were lower than 4.13 mg/L. Sodic wastes from this unit require special handling with regards to reclamation. A similar range of values was determined for in situ Luscar Formation at Cardinal River Mine (Devenny and Ryder, 1977). However, rock waste at the Cardinal River Mine shows less extreme values probably because sodium ions are displaced by calcium ions on clay exchange sites after sodic and more voluminous calcic rock wastes become mixed in dumps.

Levels of nitrogen, phosphorus, and potassium are low in the rock wastes but are comparable to those in regolith material from the same areas. Actual available phosphorus levels would be far lower than are indicated by the values plotted in Figure 20. In acidic soils, phosphorus forms nearly insoluble compounds with aluminum and iron while bonding with calcium ions in alkaline soils. Phosphorus may also bond with clay lattices by displacing hydroxyl ions (Ziemkiewicz, 1979 p. 22). However, this effect should be no more serious in rock wastes than it is within regolith material because of their similar ranges in pH.

Exchangeable cations are usually reported for pulverized samples of bedrock as a part of environmental baseline studies for open-pit mining operations. The standard ammonium acetate extraction method has been used routinely in these studies. However, this use has led to large errors in determining individual exchangeable cations and cation exchange capacity. These errors have occurred for the same reasons that they occur when this methodology is applied to regolith (see Appendix 3). In the cases of exchangeable calcium and magnesium, values as large as 314.34 and 41.45 meq/100 g, respectively, were reported by Devenny and Ryder (1977). Such values could only be regarded as reasonable if the samples were entirely vermiculite clay rather than crushed rock. Where soluble minerals are not present, under-measurement of cation exchange capacity occurs as a result of distortion of the lattices of vermiculite clays by ammonium ions during the exchange process (Fig. 11).

The values for exchangeable ions and cation exchange capacity plotted in Figure 21 were determined using the lithium acetate (LiOAc) methodology (Appendix 3). Figure 21 shows that these values for rock wastes and regolith are comparable. This result is not surprising because regolith is derived directly from the surrounding bedrock and consequently, has inherited its mineralogy and attendant chemistry. However, it must be emphasized that these analyses were carried out on the finer than 2 mm fractions of both regolith and rock wastes. Textural data previously discussed indicated that >2 mm clasts may make up extremely variable portions of both rock wastes and regolith. Consequently, values determined for exchangeable cations and total cation exchange capacity should be adjusted to reflect the content of the <2 mm fraction within the sediment being tested. Without adjustment, no meaningful comparisons of nutrient content and cation exchange capacity can be made between samples on a whole sediment basis.

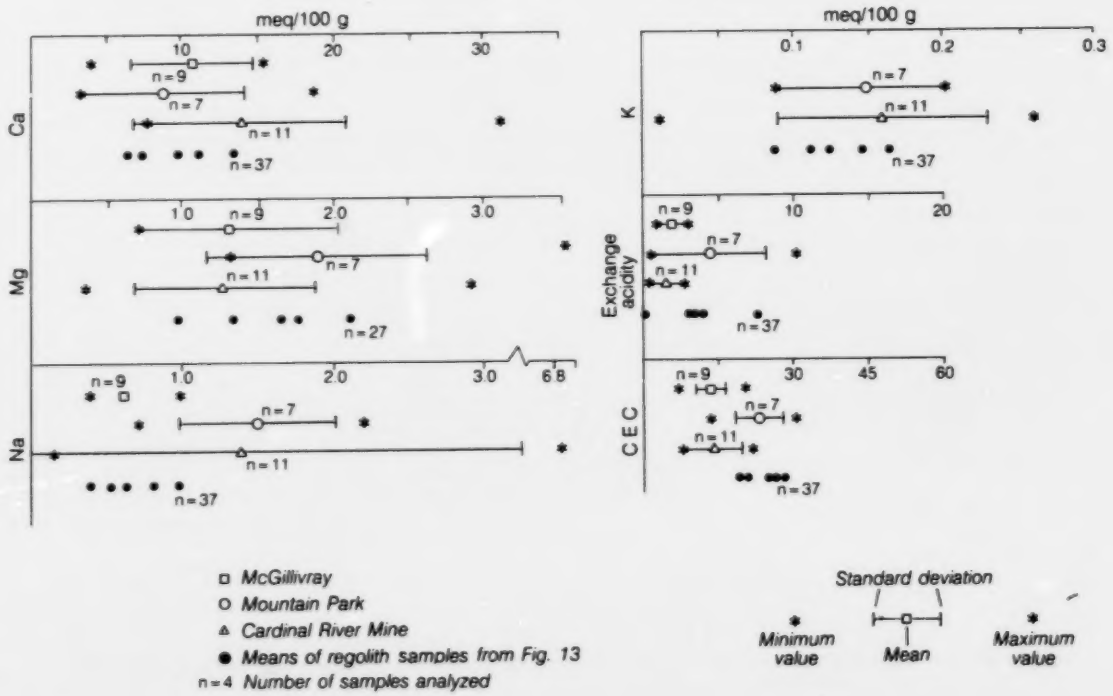


Figure 21. LiOAc-extractable cations and cation exchange capacity of rock waste samples.

CONCLUSIONS

Most previous studies related to reclamation of open-pit coal mines in the Rocky Mountain Front Ranges and Foothills have concentrated primarily on vegetation and fertilizer trials. By contrast, this study has addressed the definition and determination of selected physical and geochemical properties of natural regolith and rock wastes relevant to land reclamation within this region.

Rock waste and regolith are both coarse sediments, each with the >2 mm fraction up to 50% by weight or more. The <2 mm fraction of rock wastes usually has a higher sand content and lower contents of silt and clay than does regolith of both glacial and colluvial origin. No increase with time was detected in the chemically active <64 μm fraction of rock waste. Sites investigated had been abandoned between 10 and 60 years. Rock waste remains at low void ratios for decades. Void ratios determined on mixed regolith and rock waste and on compacted regolith at three sites reclaimed during the previous 10 years fell within the range of values for rock wastes at both the same and older sites. This result indicates that low void ratios persist in compacted regolith for periods exceeding a decade.

The mineralogy of rock waste and regolith from the coal-bearing areas of the Rocky Mountain Front Ranges and Foothills may adversely affect determination of cation exchange capacity and measurement of individual exchangeable cations. The presence of randomly interstratified vermiculite in both regolith and rock waste causes ammonium acetate extraction of cations to yield results that are erroneously low. The presence of carbonate minerals in most rock waste and regolith cause measurements of cation exchange capacity and exchangeable calcium and magnesium to be erroneously high. This latter error results from partial solubility of calcite and dolomite in the exchange medium. The combination of using lithium acetate (LiOAc) as an exchange reagent and running second extractions to determine error due to solution yielded better results.

Measurements of exchangeable cations, using the LiOAc method, and measurements of soluble cations from saturated paste extracts generally yield similar values for rock wastes from the Kootenay Group and Luscar Formation and regolith in the coal-bearing areas of the Rocky Mountain Front Ranges and Foothills. Soluble and exchangeable sodium from scattered beds in the Luscar Formation may be anomolously high. These are not significant enough in volume to require selective handling because of the calcium-rich nature of most of the Luscar Formation. Thick sodic shales in the Coalspur Beds must be handled selectively.

The textures of both regolith and rock waste should be considered when calculating the cation exchange capacities and available nutrients. Because of their coarse textures, the <2 mm fractions of these sediments may constitute less than 50% by weight. Consequently, the measurements of cation exchange and available nutrients should be adjusted according to the relative contents of >2 mm and <2 mm fractions.

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GLOSSARY

A horizon: The soil horizon formed at or near the surface. It is characterized by the accumulation of organic material and/or the removal of organic or mineral material in solution or suspension.

angle of repose: maximum angle of slope at which loose, cohesionless material will rest on similar material. In the case of waste dumps, the dump as a unit is stable at the angle of repose but the surface sediment of the dump is quasi-stable because of creep and ravelling.

B horizon: horizon of illuviation in which clays and insoluble oxides accumulate from eluviation of the overlying A horizon. The B horizon overlies the parent material **(C horizon).**

biological angle of repose: minimum angle at which creep and ravelling on the surface of rock waste dump prevents the extensive growth of vegetation.

Brunisol: a soil usually developed beneath forest and characterized by a mineral-organic A horizon and brownish or structured B horizon which lacks enrichment in clay, iron, aluminum, and organic compounds.

bulk density: mass of a sediment per unit volume.

capillary rise: height to which water will rise above a zone of saturation because of capillary action in a sediment.

cation exchange capacity: capacity of a sediment to absorb and exchange cations; it is commonly measured in milliequivalents per 100 g of sediment.

creep: slow, continuous or discontinuous, downslope movement of sediment in a rock waste dump or natural slope.

exchange acidity: measure of the exchangeable hydrogen-ion content in a sediment.

extracting reagent: solution containing a single cation used to displace other different cations from a sediment to determine the quantity of exchangeable cations contained in the sediment.

free face: steep sides of a dump down which the rock waste is tipped from a platform.

infiltration rate: maximum rate at which water can enter soil or rock waste without causing surface flow.

Luvisol: soil marked by a leached A horizon and a B horizon enriched in clay minerals.

micro-relief: closely spaced variations in surface elevation of less than 30 cm from peak to base.

organic soil horizons: horizons grading downward from fresh-to-decomposed organic detritus which overlie a soil's A horizon.

platform: flat summit of a rock waste dump.

Podzol: soil type marked by a leached A horizon and a B horizon enriched in organic material, iron and aluminum hydroxides, and clay.

reclamation: restoration of disturbed land to a state comparable to its pre-disturbed condition.

Regosol: mineral soils having horizon development too weak to meet the requirements of soils in other orders, e.g., Brunisol Luvisol.

ravelling: perceptible downslope sliding or skipping movements of individual or groups of clasts on the surface of rock waste dumps.

soil structure: combination or aggregation or primary soil particles into aggregates or clusters (peds), which are separated from adjoining clusters by surfaces of weakness (Bates and Jackson, 1980).

texture: distribution of mineral particles according to size in a sediment.

Total organic carbon: the content of organic detritus or organic compounds in soil or rock waste as determined by combustion.

APPENDIX 1

Methodology for measuring field bulk densities of soils

Density of soil in place is measured either directly by excavation of the soil and determination of its volume and dry weight or indirectly by use of radiation. Both methods encounter difficulties in dealing with stony soils. Standard equipment for fine-textured soils are inadequate for use on such sediments as stony tills and rock wastes. For example, the equipment detailed in ASTM D 1556, is only adequate for testing soils with maximum particle sizes of less than 50 mm. In the case of rock waste, maximum particle sizes are often ten times that dimension. To solve this problem, a larger sand cone device was constructed. This device is capable of measuring volumes of up to 1100 cm^3 (Fig. 1.1). The methodology used follows that outlined in ASTM D 1556. Where particles in excess of 10 cm were encountered, the test site was abandoned and relocated at an adjacent site. Relocation was done because it was found that larger particles created small cavities along the excavation margins which did not fill up with sand resulting in low density values. The minimum hole volume was 600 cm^3 in coarse rock waste. This method was preferred to a modified version of the rubber balloon method of density determination (ASTM 2167) because of the great cost of the measuring device. Radiological methods were ruled out because of the stony nature of the rock waste. It was feared that the radiological method would overrepresent the greater specific gravity of individual clasts in the rock wastes.

The large sand cone methodology was considered to be superior to the tube sampling method of Beke (1969) for use in this study for three reasons:

1) A much larger sample is taken.
2) This methodology does not involve the forcing of a tube into the soil which may increase or otherwise alter soil density.
3) Unless very large clasts are encountered, this methodology can be carried out at any site, not just those from which the tube sampler is able to extract a sample after much trial and error. Flexibility was particularly important for this study because natural soils and rock wastes were being compared. Tube bulk density sampling of rock wastes would have been impractical.

Figure 1.1. Large-capacity sand cone measuring device used to measure in situ bulk density of soil and rock waste during this study.

APPENDIX 2

Procedures for determination of sample mineralogy

Mineralogy of samples analyzed for this study was determined both on whole sediment and on clay size (<2 μm) fractions. Whole sediment samples were crushed, pelletized, and analyzed using standard X-ray diffraction (XRD) methods. Measurement of relative mineral abundance was determined from diffraction peak heights as semiquantitative estimates. In addition to abundance, diffraction peak heights vary with the type of mineral, its degree of crystallinity, crystal size, and with any amorphous material present.

Fractions for clay mineralogy identification were removed from a split of the uncrushed sediment. The clay size fraction was removed centrifugally from this split. The clay size fraction was flocculated, washed, and ionized with Ca^{+2} and K^{+} ions in the form of $CaCl \cdot 2H_2O$ and KCl. Following freeze-drying, 40 mg of each clay fraction was used to prepare a slide for XRD analysis. Slides were analyzed by XRD using a cobalt/potassium X-ray source. Constituents were ranked as major, minor, or trace according to their relative abundance as indicated by peak height. Minerals were determined on the basis of the characteristics listed below.

Nonexpandable clay minerals

Kaolinite:
(a) peaks at 7.15 Å (001) and 3.57 Å (002); and
(b) peaks disappear after heating sample to 550°C.

Chlorite:
(a) peak in area of 14 Å does not shift with glycolation and is sharpened after heating to 550°C; and
(b) peaks at 7.1 Å (002) and 3.52 Å (003) do not disappear after heating to 550°C.

Illite:
(a) peak at 10.1 Å (002) does not shift upon heating, changes in humidity, or glycolation. (The illite in all samples is a group of clay minerals not found alone but, based upon tests for expandable, mixed-layered clays, is randomly interstratified with vermiculite and smectite.)

Expandable, mixed-layer clay minerals

Vermiculite:
(a) expansion of a tail from 10 Å peak in the direction of 14 Å following heating to 100°C and placement in a nitrogen atmopshere at 1% relative humidity;
(b) expansion of a broad peak between 10 and 14 Å or the development of a peak at ~14 Å at room (35-45%) relative humidity with no further expansion upon glycolation; and
(c) rapid re-expansion at room humidity following heating to 550°C as indicated by a tail on the 14 Å side of the 10 Å peak; and
(d) collapse of mineral to 10 Å with no re-expansion following saturation with KCl.

Smectite:
(a) random interstratification of smectite (montmorillonite) with illite in the proportions of about 20-30% smectite and 80-70% illite causes the smectite 001 peak to disappear for d spacings of 17.5 Å (MacEwan et al., 1961, p. 415-418). (Most samples analyzed have illite and smectite randomly interstratified in these proportions.)
(b) smectite is confirmed by the disappearance of all peaks beyond 14 Å inclusive upon sample glycolation; and
(c) smectite is also confirmed by expansion beyond 10 Å following saturation with KCl and exposure to room humidity.

Smectite is the dominant clay mineral in some samples. Its degree of interstratification with illite has not been determined. In these samples, it is confirmed by expansion from a (001) d spacing of 14-15 Å at room humidity to 17.5 Å upon glycolation and collapse to ~10 Å with no re-expansion following heating to 500°C.

Nonclay minerals

Minerals and their diagnostic peaks are as follows:

calcite:	3.03 Å
dolomite:	2.88 Å
quartz:	3.33 Å
feldspar:	3.19 Å
pyrite:	2.73 Å.

APPENDIX 3

Procedures for measuring exchangeable cations and other soil nutrients

The presence of carbonate minerals and mixed-layer clay minerals containing vermiculite in the regolith of coal-bearing areas of the Rocky Mountains and Foothills (see Table 5) presents some difficulties in determining cation exchange capacity (CEC) and measuring exchangeable cations. Carbonate minerals contribute calcium and magnesium ions to the exchange reagent through dissolution and consequently cause values for exchangeable calcium and magnesium to be erroneously high. The use of ammonium acetate as an exchange reagent causes erroneously low values for CEC to be determined on samples containing vermiculite (A.E. Foscolos, Geological Survey of Canada, Institute of Sedimentary and Petroleum Geology, Calgary, personal communication, 1978). Vermiculite is a 2:1 expandable clay consisting of sheets of aluminum oxide/hydroxide octahedrons bounded above and below along the C-axis by sheets of silicon and aluminum oxide tetrahedrons. Each tetrahedral/octahedral "sandwich" is bounded by double layers of ordered water molecules (see Fig. 11). The extensive replacement of aluminum for silicon in the tetrahedral sheets causes vermiculite to have a negative charge. This charge is compensated for by exchangeable cations sited in the double water layer. Magnesium, calcium, and sodium ions have similar hydrated radii (5.8 Å, 4.9 Å, and 4.8Å, respectively). Potassium and ammonium ions have the much smaller hydrated radius of 1.34 Å (Barshad 1948, 1950, 1952) and, consequently, cause the water layer to collapse as depicted in Figure 11. Incomplete exchange of ammonium ion for other cations results from the distortion of the lattice edge by the ammonium ion, which prevents larger hydrated ions from leaving the water layer. The result is an erroneously low measurement of CEC and exchangeable cations.

The problems of contribution of calcium and magnesium from soluble sources and under-representation of the CEC of vermiculite and mixed-layer vermiculitic clays was remedied using the following procedure devised by Dr. A.E. Foscolos.

Step 1: the soil sample was weighed and then sandwiched between plugs of glass wool in a glass column.

Step 2: about 75 mL of distilled water was added to the sample. The sample was allowed to saturate overnight. Next day, the sample was drained and leachate was then analyzed for water-soluble Ca, Mg, K, and Na by atomic absorption analysis.

Step 3: the sample was saturated with 75 mL of LiOAc (pH 7, 1N).[1] The saturated soil was left to stand overnight and, next day, was drained as slowly as possible. The leachate was then combined with more LiOAc to make up 100 mL and was tested for Na, K, Mg, Fe, Cu, Mn, and Zn by atomic absorption analysis and for Ca by ethylenedinitrilotetra acetic acid (EDTA) titration.

Step 4: another 75 mL of LiOAc was added, was left to saturate overnight, and, next day, was allowed to drain as in step 3 after which it was combined with LiOAc to make up 100 mL. EDTA titration was then used to determine concentration of 1N LiOAc soluble Ca. Atomic absorption analysis was used to determine concentrations of 1N LiOAc soluble Mg, K, and Na. These values were substracted from those determined in step 3 to determine exchangeable Ca, Mg, K, and Na.

Step 5: 50 mL of isopropyl alcohol was added and allowed to drain. This procedure was repeated until the conductivity of the leachate was $< 40\mu$mho/cm. The alcohol leachate was discarded.

Step 6: the sample was saturated with about 75 mL of NaOAc (pH 7, 1N), was left to stand overnight and, next day, was allowed to drain as slowly as possible. The leachate was combined with NaOAc stock to make up 100 mL. The Li content of the solution was then determined by atomic absorption analysis. This value was reported as total CEC.

[1] The lithium ion has a relatively large hydrated radius (2.94 Å) and consequently does not collapse and clog the vermiculite structure during cation exchange. It is an uncommon exchangeable cation for clays in the Rocky Mountain Front Ranges and Foothills.

APPENDIX 4

Results of measurement of cation exchange capacity by ammonium acetate methodology as compared with lithium acetate methodology

The deficiencies of ammonium acetate as a reagent for displacing cations from vermiculite clays was discussed in Appendix 3. For the sake of comparison, both reagents were used to determine cation exchange capacity (CEC) and to measure exchange values for specific cations. The lithium acetate method, as described in Appendix 3, and the ammonium acetate methodology of McKeague (1976) were used. Figures 4.1A to 4.1E plot differences determined by subtracting the ammonium acetate extraction values from the lithium acetate extraction values against the pH of the sample as determined on a soil paste extract. The differences between the values determined by the two methods were predictably influenced by soil pH for total CEC and exchangeable calcium. For pH values less than 7.0 ammonium acetate values were consistently less than values determined with lithium acetate – usually 5 to 10% less although one value was nearly 30% smaller. These consistently smaller values are directly attributable to the collapsing and clogging of the vermiculite lattice by the small ammonium ions. For soils with pH values in excess of 7.0, values determined by the lithium acetate method were both greater than and lesser than ammonium acetate values because carbonates were present. The contribution of calcium to the CEC through partial solution of carbonate minerals in the ammonium acetate solution was not assessed as it was in the lithium acetate methodology. Consequently, the lower values expected for the ammonium acetate methodology were in some cases more than compensated for by cations dissolved from carbonates. Values determined for exchangeable sodium are consistently larger for the lithium acetate method. This result indicates a trapping of the sodium in the lattice by the ammonium ions and a lack of any minerals that contain soluble sodium. The values for exchangeable magnesium were always lower as determined by the lithium acetate method regardless of the sample pH. The reasons for this are not clear but may be caused by the presence of dolomite in samples having pH values greater than 7.0 and direct contribution of magnesium from the clay lattice itself. Little difference between values for potassium was noted between the two methods.

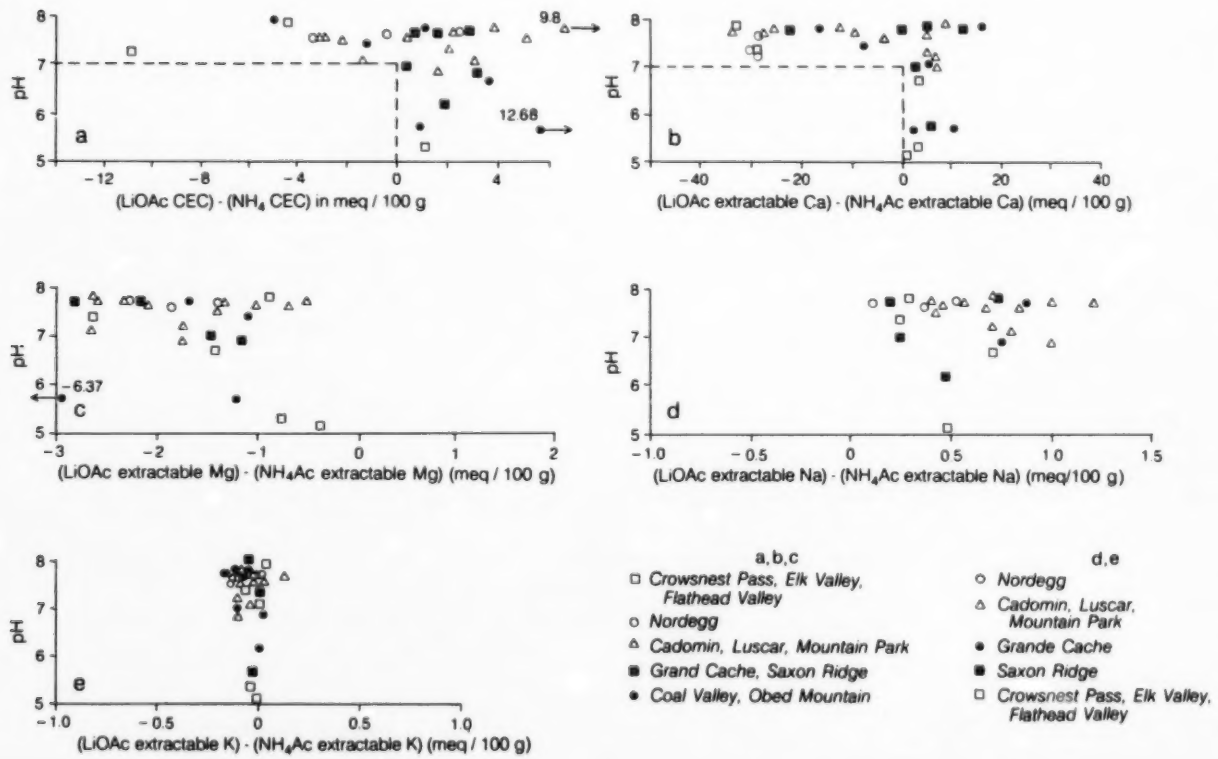

Figure 4.1. Plots of extractable cation values arrived at by lithium acetate extraction and ammonium acetate extraction vs. sample pH for samples of till and colluvium: **A)** total cation exchange capacity; **B)** extractable Ca; **C)** extractable Mg; **D)** extractable Na; **E)** extractable K.

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